

UNITED STATES OF AMERICA
DEPARTMENT OF ENERGY
FEDERAL ENERGY REGULATORY COMMISSION

IN THE MATTER OF)	
)	
Rio Grande LNG, LLC)	Docket Nos. CP16-454-000
)	CP16-454-001
)	

Motion to Intervene and Protest of City of Port Isabel, Esto’k Gna Tribal Nation of Texas, Healthy Gulf, Public Citizen, Sierra Club, and Vecinos para el Bienestar de la Comunidad Costera

On November 22, 2019, the Federal Energy Regulatory Commission (“FERC”) approved a request by Rio Grande LNG, LLC (“Rio Grande”) to construct a massive liquefied natural gas (“LNG”) export terminal capable of exporting 27 million tonnes per annum (“MTPA”) of LNG.¹ That order required that the export terminal be in service within seven years, or November 22, 2026.² However, despite FERC’s initial approval, Rio Grande has failed to attract the customers necessary to reach a final investment decision and go forward with the project. Now, Rio Grande seeks to extend its deadline for construction and operation by two years to November 22, 2028.

This project is in a very different situation than the typical project requesting an extension, because the whole project is already up in the air and subject to FERC reconsideration. —The underlying certificate for this project is already on remand to FERC, and FERC is additionally considering multiple proposed revisions to this project and the associated pipelines. Thus, whereas FERC has argued that an extension request, itself, may not be ground for revisiting prior conclusions about need, the public interest, *etc.*, here, those issues pending before FERC regardless of this request for an extension. But the current extension request, which arises because the project has, for years, failed to secure customers and thus reach a final investment decision, is still further evidence that the project is contrary to the public interest and should be denied.

¹ *Rio Grande LNG, LLC*, 169 FERC ¶ 61,131 (2019) (“Certificate Order”), *order on reh’g*, 170 FERC ¶ 61,046 (2020).

² *Id.* at ¶ 135.

As we further explain below, the extension request and the project as a whole should be denied. And while FERC's notice states FERC's normal goal of "acting on the [extension] request within 45 days,"³ at a minimum, FERC cannot grant the extension request here while review of the underlying project remains pending.

I. Intervention

We support FERC's decision to notice this extension request in the existing docket for this facility, rather than to open a new docket. In the past, FERC has suggested that parties who had already intervened in an initial certificate proceeding would need to intervene in a new docket regarding an extension. Our understanding is that such repeated intervention is not required here, where the extension request will be considered in the initial docket. However, because FERC's notice, Accession 20220412-3060, is not explicit in this regard, in an abundance of caution, parties to the initial proceeding (City of Port Isabel, Vecinos para el Bienestar de la Comunidad Costera, and Sierra Club) are submitting renewed interventions here. In the future, FERC should be explicit about whether such repeated intervention is necessary.

A. Intervention of City of Port Isabel

Pursuant to 18 C.F.R. § 385.203(b)(1)-(2), the City of Port Isabel, Texas states that the exact name of the movant is the City of Port Isabel, and the movant's principal place of business is 305 E. Maxan St., Port Isabel, TX 78578.

Pursuant to 18 C.F.R. § 385.203(b)(3), the City of Port Isabel identifies the following persons for service of correspondence and communications regarding this application:

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³ Accession 20220412-3060 at 2.

City of Port Isabel (“City”) previously intervened in this docket⁴ and should be granted intervention again here.

The City, a Texas municipal corporation chartered in 1928, is located in Cameron County, Texas along the shores of the Laguna Madre. In 2014, the American FactFinder recorded the City’s population as 5,022. Principal industries in the City include fishing, tourism and shipping and light industries associated with the Port Isabel-San Benito Navigation District. Visitors to the City would pass by this project before arriving to the City, and elements from the project will be visible from the City.

As a community dependent on tourist spending, the aesthetic appeal of the surrounding area is economically vital. City residents employed in the fishing and tourism industries use waters and other natural environments commercially that may be impacted by the project, while other city residents use potentially impacted waters and environments for recreational purposes. The City, including its schools, housing and health care facilities, are located in close proximity to the project site, and subject to potential adverse health and safety impacts, including emissions, dust, noise and light generated from daily operations, as well as technological hazards associated with potential incidents at the project site. The proximity of the project to the City’s transportation infrastructure, including the Brazos Santiago Pass, Gulf Intracoastal Waterway and Port Isabel Ship Channel and Turning Basin, as well as State Highways 100 and 48 expose the City to potential transportation disruption caused by operations or incidents at the project site. Furthermore, the City is highly dependent on revenues collected from property and sales taxes, and any decline in property values or in tourist visits will result in economic harm to the City.

In addition to impacts related to the project’s location in relation to the City, the City also potential adverse impacts by this project on cultural and environmental resources located at or adjacent to the project site, including the potential for takings of West Indian Manatees within the Brazos Santiago Pass and the Brownsville Ship Channel, and impacts upon the Bahia Grande unit of the Laguna Atascosa Wildlife Refuge, which houses endangered species such as the Ocelot, Jaguarundi, and numerous bird and plant species; and which has also been the site of discoveries of artifacts of ancestral Native peoples and original peoples, including Esto’k Gna, human peoples.

⁴ Accession Nos., 20160609-5279, 20170517-3057.

The City reasonably believes that the project will impact these precious cultural and environmental resources, which are of significance to Port Isabel residents. The City reserves the right to add or amend elements related to its standing to intervene in this proceeding.

Accordingly, the City has a direct and substantial interest in this matter and may be directly impacted by the outcome of this proceeding. The City cannot be adequately represented by any other party and may be adversely affected or bound without opportunity to present its position unless it's permitted to intervene in this proceeding. Moreover, the City's participation in this proceeding is in the public interest. Good cause exists to grant the City's motion to intervene.

Pursuant to 18 C.F.R. § 385.203(b)(1)-(2), the City's position is that this request for an extension of time should be denied by FERC.

B. Intervention of Esto'k Gna Tribal Nation of Texas

Pursuant to 18 C.F.R. § 385.203(b)(1)-(2), the Esto'k Gna Tribal Nation of Texas ("the Tribe") states that the exact name of the movant is Esto'k Gna Tribal Nation of Texas.

Pursuant to 18 C.F.R. § 385.203(b)(3), the Esto'k Gna Tribal Nation of Texas identifies the following persons for service of correspondence and communications regarding this application:

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The Tribe should be granted intervention pursuant to 18 C.F.R. § 385.214(b)(2)(ii). The location of the Rio Grande LNG project prevents the Tribe and its members from accessing sacred lands and offering their prayers. Alternatively, and separately, the Tribe's intervention is in the public interest and should be granted pursuant to 18 C.F.R. § 385.314(b)(2)(iii).

Pursuant to 18 C.F.R. 385.203(b)(1)-(2), the Tribe's position is that this request for an extension should be denied that the underlying certificate should be vacated because it is clear that the project will not be completed by the deadline imposed therein.

C. Intervention of Healthy Gulf

Pursuant to 18 C.F.R. § 385.203(b)(1)-(2), Healthy Gulf states that exact name of the movant is Healthy Gulf, and the movant's principal place of business is 935 Gravier Street, Suite

700, New Orleans, LA 70112.

Pursuant to 18 C.F.R. § 385.203(b)(3), Healthy Gulf identifies the following persons for service of correspondence and communications regarding this application:

Naomi Yoder
Staff Scientist
Healthy Gulf
P.O. Box 66226
Houston, TX 77266
504-525-1528 x213 (tel)

Cynthia Sarthou
Executive Director
Healthy Gulf
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New Orleans, LA 70112
(504) 525-1528 x202 (tel)

Healthy Gulf should be granted intervention pursuant to 18 C.F.R. § 385.214(b)(2)(ii). Healthy Gulf is a 501(c)(3) organization with over 2,400 members in Texas. If this project goes forward, many of these members could be impacted by effects on water, air pollution, noise, etc. Separately and alternatively, Healthy Gulf's intervention would be in the public interest as provided by 18 C.F.R. § 385.314(b)(2)(iii). Healthy Gulf has expertise concerning the environmental impacts of LNG export facilities that are constructed and operate around the Gulf Coast. Additionally, Healthy Gulf also has expertise concerning the impacts of LNG export facilities that are constructed and operate around the Gulf Coast on environmental justice communities. Finally, Healthy Gulf employs staff members who work to protect the integrity of wetlands, waters, wildlife, and other ecological resources throughout the Gulf Region. This work will be directly affected by the construction and operation of these proposed facilities.

Pursuant to 18 C.F.R. § 385.203(b)(1)-(2), Healthy Gulf's position is that the request for an extension should be denied, and that the underlying certificates should be vacated without prejudice because it is clear that the project will not be completed by the deadline imposed therein.⁵

D. Intervention of Public Citizen

Established in 1971, Public Citizen is a national, not-for-profit, non-partisan, research and advocacy organization representing the interests of household consumers. Public Citizen is active

⁵ While Healthy Gulf has not previously intervened in this docket, Healthy Gulf's intervention and the content of its protest are allowable under the new policy announced by FERC in *Adelphia Gateway*. 178 FERC ¶ 61,030 P10 (Jan. 20, 2022).

before FERC promoting just and reasonable rates, and supporting efforts for both gas and electric utilities to be accountable to the public interest. Public Citizen has a Texas field office, with full time staff and a director serving the interests of its Texas-based membership. Public Citizen has filed a doc-less motion to intervene in this docket⁶ and includes the following additional information.

Pursuant to 18 C.F.R. § 385.314(b)(1), Public Citizen states that its position is that this request for extension should be denied; that if FERC approves the extension, additional NEPA review is necessary, and if FERC approves the extension, FERC must consider requiring additional mitigation measures. These positions are further described in the following protest, and Public Citizen expects to further develop its position as this proceeding progresses.

Pursuant to 18 C.F.R. § 385.314(b)(2), Public Citizen should be permitted to intervene because its public participation would be in the public interest, as recognized by subparagraph (b)(2)(iii).

Pursuant to 18 C.F.R. § 385.203(b)(1)-(2), Public Citizen states that the exact name of the movant is the Public Citizen, Inc., and the movant's principal place of business is 215 Pennsylvania Ave SE, Washington, DC 20003.

Pursuant to 18 C.F.R. § 385.203(b)(3), Public Citizen identifies the following persons for service of correspondence and communications regarding this extension request:

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E. Intervention of Sierra Club

Sierra Club has already been granted intervention in this proceeding.⁷

Sierra Club is the nation's largest grassroots environmental organization, is dedicated to the protection of the natural environment and public health, and has a longstanding interest and

⁶Accession No. 20220418-5121.

⁷ *Id.* at ¶ 15. *See also* Secretary's May 17, 2017 Notice Granting Interventions.

expertise in LNG export facilities around the Gulf of Mexico generally and Brownsville, Texas specifically. Sierra Club's intervention is in the public interest, as provided by as provided by 18 C.F.R. § 385.314(b)(2)(iii). Sierra Club has experience with FERC's obligation and authority regarding greenhouse gas emissions, and as FERC works to develop its policy in this area, FERC and the public will benefit from Sierra Club's participation in individual dockets and Sierra Club's perspective. Sierra Club also provides an important perspective on FERC procedures, and Sierra Club's participation will benefit the public as FERC develops post-*Algonquin* procedures for handling extension requests, interventions, etc.

Separately and alternatively, Sierra Club should be granted intervention because its members' interests will be directly affected by the proceeding. 18 C.F.R. § 385.214(b)(2)(ii). As of March 31, 2022, Sierra Club has more than 26,000 members in Texas. If the LNG export facility is built and operated, many of these members will be impacted by effects on water, air pollution, noise, etc.

Sierra Club has demonstrated the vitality of these interests in many ways, including Sierra Club's participation in prior proceedings concerning this export facility and its related pipeline before FERC, the United States Court of Appeals for the District of Columbia Circuit, and the United States Court of Appeals for the Fifth Circuit. More broadly, Sierra Club runs national advocacy and organizing campaigns dedicated to reducing American dependence on fossil fuels, including natural gas, and to protecting public health. These campaigns, including its Beyond Coal and Dirty Fuels campaigns, are dedicated to promoting a swift transition away from fossil fuels and towards reducing global greenhouse gas emissions.

Sierra Club therefore satisfies the conditions for intervention both as representatives of interested consumers and because their participation is in the public interest. See 15 U.S.C. § 717n(e); 18 C.F.R. § 385.214(b)(2).

Pursuant to 18 C.F.R. § 385.203(b)(1)-(2), Sierra Club states that the exact name of the movant is the Sierra Club, and the movant's principal place of business is 2101 Webster Street, Suite 1300, Oakland, CA 94612.

Pursuant to 18 C.F.R. § 385.203(b)(3), Sierra Club identifies the following persons for service of correspondence and communications regarding this application:

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415-977-5779

Pursuant to 18 C.F.R. § 385.314(b)(1), Sierra Club's position is that the request for an extension should be denied, and that the underlying certificate should be vacated because it is clear that the project will not be completed by the deadline imposed therein.

F. Intervention of Vecinos para el Bienestar de la Comunidad Costera

VBCC has already been granted intervention in this docket.⁸ To the extent that VBCC must intervene again to protest this request for an extension, VBCC does so here and provides the following information.

Pursuant to 18 C.F.R. § 385.203(b)(1)-(2), VBCC states that the exact name of the movant is Vecinos para el Bienestar de la Comunidad Costera.⁹

Pursuant to 18 C.F.R. § 385.203(b)(3), VBCC identifies the following persons for service of correspondence and communications regarding this application:

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VBCC should be granted intervention pursuant to 18 C.F.R. § 385.214(b)(2)(ii). VBCC is an unincorporated association of residents of Laguna Heights, Texas and nearby areas that seeks to protect and improve the health, standard of living, and economic development of the coastal community in the Rio Grande Valley of South Texas. The members of VBCC are largely low-income, Hispanic families whose livelihoods depend on the continued vibrancy of existing locals

⁸ Accession No. 20170517-3057.

⁹ VBCC is an unincorporated association and, thus, does not have a principal place of business.

industries, such as fishing and hospitality. VBCC's members will be directly and materially affected by the proposed project, and FERC's ultimate decision on this extension request, based on their close proximity to the proposed export facility and the harmful impacts the facility will have on their livelihoods, health, and properties. VBCC has concerns about the location, size, and safety of the project among other concerns. VBCC is also concerned about the environmental and health impacts related to construction and operation of the project, specifically the local air pollution created by the project and the safety risk from fires, explosions, or other accidents. Within VBCC, there are members who have health conditions, such as asthma, that will make them especially sensitive to the impacts associated with the project. The project will add an aesthetically unattractive feature to an existing natural viewscape, that will be visible from most members' residences and will emit additional light and noise. It is believed that members' property values will be negatively affected by the project.

The project lies within three to four miles of the residences of VBCC members. Several members of VBCC attend school approximately three miles from the project area. VBCC members work or travel to work within three miles of the project site, including in the fishing and hospitality industries. It is believed that these industries that members work in will be negatively impacted by the proposed project due to the marine impacts from the facility, increased tanker traffic, exclusion zones and a reduction in tourism. These impacts are particularly harmful to low-income families such as VBCC's members who already face barriers to economic opportunity and health services.

Moreover, the impacts of the project to VBCC members' health, standard of living, and economic development should be considered in conjunction with the other contiguous and contemporaneous LNG project proposed for the Port of Brownsville: Texas LNG Brownsville, Docket No. CP16-116-000. The cumulative impacts of these projects would be significant for VBCC members who live in close proximity to the facilities.

In addition to being directly impacted, the interests VBCC represents here, including health, economic, and environmental interests, are shared by the public at large, such that VBCC's intervention is in the public interest as provided by 18 C.F.R. § 385.314(b)(2)(iii).

II. Protest

As noted above, this request differs from the typical extension request because the underlying certificate is on remand to FERC for reconsideration.¹⁰ That remand provides authority for FERC to reevaluate the certificate as a whole.¹¹ And such broad reconsideration is appropriate, both in order to properly balance the issues identified in *Vecinos*, and in light of the numerous other changes that have been proposed to the Rio Grande terminal and the Rio Bravo pipelines.

This context alters FERC's evaluation of the extension request. Normally, in evaluating a request for an extension, FERC considers whether the applicant has shown good cause¹² and whether the findings underlying the initial certificate have gone stale.¹³ Here, as we explain below, Rio Grande has failed to show good cause. But on the second factor, the question isn't merely whether presumptively-valid prior findings have gone stale, because many of those prior findings have already been found to be unsupported by the D.C. Circuit or have been superseded by proposed changes in the project.

Here, Rio Grande has failed to satisfy either requirement for an extension. Accordingly, for either or both of these reasons, the request for an extension must be denied.

¹⁰ *Vecinos para el Bienestar de la Comunidad Costera v. FERC*, 6 F.4th 1321 (D.C. Cir. 2021).

¹¹ *TransCanada PipeLines Ltd. v. FERC*, 24 F.3d 305, 308 (D.C. Cir. 1994)

¹² See, e.g., *Chestnut Ridge Storage LLC*, 139 FERC ¶ 61149, 62133 (2012) (“In addition to the potential for information and data to become dated, there could potentially be anti-competitive implications associated with granting project sponsors extensions of time to construct authorized projects based primarily upon the projects' inability to garner market support. The fact that one company already holds a certificate for a project, even if it hasn't started construction, could inhibit a potential competitor from pursuing its own project to serve the same market, since the certificate holder, having already received Commission authorization to proceed with its project, could conceivably begin construction at any time.”).

¹³ *Const. Pipeline Co., LLC Iroquois Gas Transmission Sys., L.P.*, 165 FERC ¶ 61081 P9 (Nov. 5, 2018); accord *Algonquin Gas Transmission, LLC*, 170 FERC ¶ 61144, P15 (2020) (“the purpose of establishing a deadline for the completion of construction is to diminish the potential that the public interest might be compromised by significant changes occurring between issuance of the certificate and commencement of the project.”) (internal quotation and modification omitted).

A. Rio Grande Has Not Shown Good Cause for an Extension

Each certificate order includes a completion date that “provides what the Commission believes—based on its assessment of circumstances relevant to the specific project—to be a reasonable period of time for the project sponsor to conclude any necessary marketing efforts, complete construction, and make the project available for service.”¹⁴ A showing of good cause is required *even if* the extension request is filed “within a timeframe during which the environmental and other public interest findings underlying the Commission’s authorization can be expected to remain valid.”¹⁵ To satisfy the good cause standard, the applicant must show that it “made good faith efforts to meet its deadline but encountered unforeseeable circumstances,”¹⁶ typically delays in issuance of other needed permits.¹⁷ In evaluating good cause, FERC should follow the principles articulated in *Chestnut Ridge Storage*, 139 FERC ¶ 61149, 62134 P13 (2012), wherein FERC explained that “recent experiences” caused FERC to reevaluate prior practices regarding extensions.

Chestnut Ridge explained that an applicant failed to show “good faith efforts” to complete a project where the applicant “set its certificate on a shelf and let it lie dormant,” rather than being “actively engaged in preparations in anticipation of commencing construction.”¹⁸ In *Chestnut Ridge*, the applicant had not commenced construction based on the apparent determination that the “project was not financially viable under current conditions.”¹⁹ FERC concluded that a voluntary decision not to proceed with construction based on “market-related” setbacks was fundamentally different than other types of setbacks, such as firm barriers to construction.²⁰ Accordingly, FERC concluded that the applicant had failed to show good cause, denied the

¹⁴ *Arlington Storage Co., LLC*, 155 FERC ¶ 61,165 P8 (2016).

¹⁵ *Id.*

¹⁶ *Const. Pipeline Co., LLC Iroquois Gas Transmission Sys., L.P.*, 165 FERC ¶ 61081 P9 (2018)

¹⁷ *See, e.g., id.* P9 n.32 (collecting FERC decisions).

¹⁸ *Id.* P18.

¹⁹ *Id.* P11.

²⁰ *Id.* P13.

request for an extension, and vacated the underlying certificate without prejudice.²¹

In contrast with *Chestnut Ridge*, in modern cases where FERC has found good cause, the applicant was typically actively working to complete the project, but some outside force other than a lack of market support prevented the applicant from doing so. This is not such a case. Although there has been extensive litigation regarding the project, no agency or court has entered any sort of stay or injunction. Indeed, even when FERC's issuance of the certificate was found to be arbitrary, Rio Grande persuaded the D.C. Circuit not to issue the "ordinary remedy" of vacatur, instead prevailing in a request to leave the certificate in place, specifically so as to avoid delaying the project.²² Similarly, in this docket, Rio Grande has opposed requests for additional analysis and process, such as to consider changed circumstances at the Space X facility close to the Rio Grande facility site,²³ or regarding Rio Grande's proposed carbon capture and sequestration ("CCS"), arguing that "RGLNG is working very hard to commence construction of the RGLNG Terminal" and that delay would hinder these efforts.²⁴

Despite previously arguing against actions that would have paused Rio Grande's clock and insisting that any action that may delay Rio Grande's progress was untenable,²⁵ Rio Grande seeks this extension. This request is facially self-contradictory—Rio Grande fought for a running clock and got it. As a result, Rio Grande was free to proceed and commence construction. To be clear, Protestors' position is that the project should have been stayed in each of these circumstances and that construction should not have commenced prior to resolution of the various legal and technical issues presented by the project. But it is obviously self-contradictory for Rio Grande to argue that a stay or delay would cause it harm by halting progress on the project, then not move forward with the project by choice. This undercuts Rio Grande's assertion that it has

²¹ *Id.* P26.

²² *Vecinos*, 6 F.4th at 1325.

²³ *See* Accession No. 20210506-5091.

²⁴ Accession No. 20220110-5107 at 5, 34-35.

²⁵ While denigrating and questioning the motives of those it disagreed with. *See* Accession No. 20220110-5107 at 34-35 ("new public hearings would serve no purpose at this time other than to allow disingenuous and inequitable opposition to RGLNG another opportunity to delay the project").

“worked diligently to continue to develop” the project.²⁶ Every time Rio Grande argued against a stay or delay, it suggested that, absent a stay, it would be willing to begin construction while proceedings were pending. If Rio Grande was unwilling or unable to construct while proceedings were pending without a stay, a stay would not have harmed Rio Grande. But Rio Grande has obviously not begun construction. Instead, Rio Grande vigorously and successfully opposed imposition of the types of barriers that FERC has previously recognized as constituting good cause for an extension.

Here, Rio Grande’s sole attempt at establishing good cause of an extension is the brief impact that the COVID-19 pandemic had on the global LNG market.²⁷ But Rio Grande had sought, but failed to acquire, customers for years prior to the COVID-19 pandemic. And while Rio Grande argues that it has secured some additional customers this year,²⁸ as the pandemic ebbs, Rio Grande does not assert that these customers are sufficient to support the project, and Rio Grande *still* has not made a final investment decision and does not anticipate doing so until later this year.²⁹ This is precisely the kind of voluntary, market-driven delay that FERC found insufficient to support good cause in *Chestnut Ridge*.³⁰

We recognize that in *Adelphia*, FERC explained the COVID-19 pandemic contributed to

²⁶ Request for Extension at 1.

²⁷ Request for Extension at 2. Rio Grande solely points to market disruption, and does not argue that COVID-19 pandemic made it difficult to proceed with construction due to worker safety, supply chain, and other practical issues. Nor could Rio Grande so argue: had not attempted to commence construction, and still has not reached a final investment decision or sought to start construction.

²⁸ *Id.*

²⁹ Harry Weber, *Rio Grande LNG project final investment decision delayed to second half of 2022*, S&P Global, Jan. 3, 2022, <https://www.spglobal.com/commodityinsights/en/market-insights/latest-news/lng/010322-rio-grande-lng-project-final-investment-decision-delayed-to-second-half-of-2022> (attached).

³⁰ To the extent that the applicant suggests that its carbon capture and sequestration (“CCS”) proposal indicates an effort to move the project forward and justifies good cause for an extension, Protestors disagree. Without commenting on the merits of that particular application or CCS in general, it is irrelevant to the specific question of whether good cause exists for an extension because it is not related to whether the applicant made sufficient efforts to bring the project online or whether the applicant remains sufficiently committed to the project.

“good cause” for a delay in construction. *Adelphia* PP19-20. But there, the impact of COVID-19 was to physically disrupt construction activities and to delay issuance of necessary permits, rather than to frustrate development of market support. *Id.* And while FERC accepted COVID-19’s impact on markets as part of the good cause demonstration for *Delfin LNG*, 178 FERC ¶ 61,031 PP21-22, FERC’s reasoning there was unpersuasive and should not be followed here; as FERC emphasized, FERC will review “extension requests on a case-by-case-basis.” *Id.* P22.

There are sound policy reasons for FERC to continue to require good cause, independent of questions of stale findings, in evaluating extension requests. As recognized in *Chestnut Ridge*, allowing certificate holders to leave certificates “on a shelf” risks permitting anticompetitive behavior that “introduce[s] or perpetuate[s] market inefficiencies.”³¹ Pertinent to intervenors’ interests, allowing LNG export authorization holders to sit on dormant projects prevents FERC, the Department of Energy, and others from properly assessing the cumulative impact of already-approved projects when evaluating future proposals. And these impacts can be severe. As FERC has recognized, LNG exports are presently the “primar[y]” source of demand that is driving large increases in U.S. gas prices.³² The impacts of these increases fall particularly hard on low-income, Black, Hispanic, and Native American households, which statistically face dramatically higher energy burdens—spending greater portions of their income on energy bills—than the average household.³³

Perhaps sensing that the reason it has not commenced construction is not good cause for an extension, Rio Grande attempts to exploit Russia’s invasion of Ukraine. Rio Grande’s

³¹ 139 FERC ¶ 61,149 PP9, 18.

³² FERC, Winter Energy Market and Reliability Assessment (Oct. 21, 2021) at 2, available at <https://ferc.gov/sites/default/files/2021-10/Winter%20Assessment%202021-2022%20-%20Report.pdf> (attached); accord *id.* at 11. See also Clark Williams-Derry, IEEFA U.S.: Booming U.S. natural gas exports fuel high prices, IEEFA.ORG (Nov. 4, 2021), <https://www.energy.gov/sites/default/files/2021-12/Williams-Derry%2C%20Booming%20Export%20Prices.pdf> (attached).

³³ American Council for an Energy-Efficient Economy, *How High are Household Energy Burdens?* (Sept. 2020), available at <https://www.aceee.org/sites/default/files/pdfs/u2006.pdf> (attached). Accord Eva Lyubich, *The Race Gap in Residential Energy Expenditures* (June 2020), available at <https://haas.berkeley.edu/energy-institute/research/abstracts/wp-306/#:~:text=Black%20households%20have%20higher%20residential,status%2C%20and%20city%20of%20residence> (attached).

contention that it will be able to contribute to the United States' short-term efforts to increase LNG shipments to Europe as it transitions from dependence on Russian LNG is absurd on its face. The United States has not committed to shipping LNG from any particular sources or at any particular volumes.³⁴ But, what is clear, is that shipping LNG to Europe is not a long-term policy. In the agreement cited by Rio Grande, LNG exports are being paired with European measures to reduce energy demand and a long-term commitment to achieving greenhouse gas emissions targets.³⁵ Satisfying this agreement will not require construction of any LNG export infrastructure that is not already under construction.³⁶

The facilities at issue here would come on-line too late to be helpful to Europe. Obviously, Rio Grande is attempting to extend its construction deadline to November 2028. Rio Grande is not likely to hit this target either and will likely need another extension. As explained above, it has not reached a final investment decision yet. Construction will take approximately six years.³⁷ This is already cutting it tight for completion of construction in November 2028. But consider that this project is currently the subject of active litigation in the United States Court of Appeals for the Fifth Circuit³⁸ and, as explained in more detail below, still requires numerous approvals from FERC.

Rather than supporting Rio Grande's extension request, the presence of the United States-Europe LNG export agreement underscores why Rio Grande's extension should not be granted. As explained above, one of the policies advanced by this good cause inquiry is to avoid distortion

³⁴ See White House Press Release, *FACT SHEET: United States and European Commission Announce Task Force to Reduce Europe's Dependence on Russian Fossil Fuels*, available at <https://www.whitehouse.gov/briefing-room/statements-releases/2022/03/25/fact-sheet-united-states-and-european-commission-announce-task-force-to-reduce-europes-dependence-on-russian-fossil-fuels/>.

³⁵ *Id.*

³⁶ See generally Clark Williams-Derry, *The U.S. Can Increase LNG Exports to Europe: No New Contracts or Infrastructure Are Required*, IEEFA (Apr. 2022), available at <https://ieefa.org/ieefa-analysis-finds-u-s-can-increase-lng-shipments-to-europe-without-building-new-facilities/> (attached).

³⁷ Accession No. 20190426-3020 at 2-32 – 2-33 (table showing construction schedule).

³⁸ See Accession No. 20211119-5044.

of markets³⁹ and, by extension, to ensure that the relevant stakeholders can properly assess those markets. It is hard to imagine a more important context within which the LNG market must be properly assessed with granularity and certainty. Here, the United States and Europe are attempting a challenging feat—a short-term expansion of fossil fuel exports to Europe while still meeting applicable greenhouse gas emissions targets. Not meeting these emissions targets would, as the Commission is aware, be dire.⁴⁰ Thus, it is imperative that markets not be distorted now and that information concerning whether a given facility will indeed come online be as accurate as possible. Providing Rio Grande this extension despite the fact that significant demand has not materialized for its facility would undermine efforts to assist Europe while ensuring that emissions targets are not exceeded.

Ultimately, this case is clearly more like *Chestnut Ridge* than other cases in which FERC found good cause for an extension. Rio Grande seeks an extension because, essentially, it did not begin construction as a result of a brief market downturn. In reality, Rio Grande did not begin construction either because it chose not to or because there was insufficient demand for Rio Grande's project. Neither of these constitute good cause under FERC's precedents. But, even if a brief market downturn were the reason for Rio Grande's struggles, Rio Grande still has not established good cause. A mere market downturn is not a sufficient justification for an extension under FERC's precedents.⁴¹

B. Changed Circumstances Provide an Additional and Alternative Ground for Denying the Extension Request, or at a Minimum, Demonstrate the Need for Additional Review

Second, if an applicant has shown good cause, FERC must address whether subsequent factual developments undermine or require revisiting FERC's prior findings. "If the service authorized by a certificate is not initiated within the time period specified in the certificate, it

³⁹ *Chestnut Ridge Storage LLC*, 139 FERC ¶ 61149, 62133 (2012).

⁴⁰ See IPCC, *Climate Change 2022 Impacts, Adaptation and Vulnerability: Summary for Policy Makers SPM-20* (Feb. 2022), available at <https://www.ipcc.ch/report/sixth-assessment-report-working-group-ii/> ("If global warming temporarily exceeds 1.5°C in the coming decades or later (overshoot), then many human and natural systems will face additional severe risks, compared to remaining below 1.5°C.") (attached).

⁴¹ *Chestnut Ridge*, 139 FERC ¶ 61,149, P13.

cannot be presumed that the public convenience and necessity still require the project.”⁴²

Even if FERC determines that the applicants have shown good cause for an extension, FERC must address whether it’s prior findings have been “compromised by significant changes occurring between issuance of the certificate and commencement of the project.”⁴³ Accordingly, “parties must have the right to argue that developments since the issuance of the certificate have called into question the Commission’s finding of public convenience and necessity.”⁴⁴ Generally, in reviewing an extension request, FERC will “not relitigate the Commission’s decision to issue a certificate, including whether the Commission properly found the project to be in the public convenience and necessity.”⁴⁵ Instead, FERC generally only considers new or changed circumstances that occurred after FERC’s initial approval.⁴⁶

At the threshold, FERC’s general policy limiting its review of this extension request to new or changed circumstances should not apply here. FERC’s initial decision to issue this certificate is already before the commission after the D.C. Circuit held that FERC’s initial approval was insufficient and remanded to FERC.⁴⁷ Now FERC plainly has broad authority to reconsider and re-evaluate the certificates underlying this extension request. In *TransCanada Pipelines Ltd v. FERC*, 24 F.3d 305, 308 (D.C. Cir. 1994), the D.C. Circuit remanded, without vacatur, FERC orders regarding the expansion of a pipeline.⁴⁸ On a subsequent appeal, the court explained that “once FERC reacquired jurisdiction, it had the discretion to reconsider the whole of its original discretion.” *Se. Michigan Gas Co. v. FERC*, 133 F.3d 34, 38 (D.C. Cir. 1998). The same is true here and FERC should adjust its approach to this extension request accordingly.

FERC now has before it multiple proceedings related to this project. In addition to this requested extension, FERC has outstanding obligations to consider:

⁴² *Wyoming-California Pipeline Co.*, 70 FERC ¶ 61041, 61130 (1995).

⁴³ *Constitution Pipeline Co.*, 165 FERC ¶ 61,081, at ¶ 9 (Nov. 5, 2018).

⁴⁴ *Algonquin Gas Transmission, LLC*, 170 FERC ¶ 61,144, Dissent of Comm’r Glick P9 (2020).

⁴⁵ *Adelphia Gateway*, 178 FERC at P10.

⁴⁶ *Id.*

⁴⁷ *Vecinos*, 6 F.4th at 1325.

⁴⁸ *See Great Lakes Gas Transmission Ltd. P’ship*, 72 FERC ¶ 61,081, 61,431 (1995) (FERC explaining, on remand, that remand had been without vacatur).

- In dockets CP16-454 and CP16-455, the climate and environmental justice impacts of the entire Rio Grande LNG export terminal and Rio Bravo pipeline system, pursuant to the remand in *Vecinos*.
- In those same dockets, the overall questions of whether the terminal and pipeline systems are consistent with the public interest or required by the public convenience and necessity, in light of FERC's forthcoming additional analysis of climate and environmental justice issues.
- In docket CP20-481, Rio Bravo's proposal to substantially redesign the Rio Bravo pipeline system, and comments from Shrimpers and Fishermen of the RGV *et al.* arguing that these changes, as well as cancellation of the Annova LNG project,⁴⁹ demonstrate that a single pipeline could satisfy the project purpose.
- In docket CP21-17, Rio Grande's proposal to add CCS equipment to its LNG export terminal.
- Further potential design changes, *e.g.*, in response to the changes in the reinstated Clean Water Act section 404 permit.⁵⁰

All these issues pertain to the same overall project, and it would be unjustified and frankly infeasible for FERC to attempt to consider each in isolation. Nor is it what Rio Grande purports to desire. For example, Rio Grande and Rio Bravo appear to agree that FERC should consider the emission mitigations and reductions proposed in dockets CP22-17 and CP20-481 as part of the remand in dockets CP16-454 and CP16-455. Given how many aspects of these interrelated projects are subject to ongoing FERC review, if FERC does not deny the extension request and vacate its underlying approvals, FERC should suspend and comprehensively reconsider those approvals.

⁴⁹ See Accession No. 20210335-5212.

⁵⁰ See Accession No. 20211006-5120. The modified permit authorizes impacts to fewer acres of wetlands than discussed in the final EIS. As of this writing, we have been unable to determine whether this change solely reflects the changes proposed in CP20-481, or additional changes as well.

If FERC opts for the latter approach, it must pay particularly close attention to several significant considerations, many of which have changed significantly since FERC's initial approval of this project.

1. FERC Must Revisit the Impact of this Project on Climate Change

What was frightening when FERC initially approved this project is now dire as more information about climate change and associated impacts has been made available to the public.⁵¹ According to the most recent report from the Intergovernmental Panel on Climate Change, if global warming is to be limited to 1.5° C significant action must commence now. The previous decade featured the highest average annual greenhouse gas emissions relative to any previous decade.⁵² Achieving climate change targets necessarily involves “rapid and deep and in most cases immediate GHG emission reductions in all sectors.”⁵³ In the energy sector, this entails “a substantial reduction in overall fossil fuel use, the deployment of low-emission energy sources, switching to alternative carriers, and energy efficiency and conservation.”⁵⁴

In issuing the initial Section 3 and Section 7 certificates, FERC explicitly refrained from making any determination of the significance of project greenhouse gas emissions, based on the claim that FERC lacked the tools to do so.⁵⁵ The D.C. Circuit decided that this greenhouse gas emissions analysis was insufficient.⁵⁶ And, since issuing the certificate, the United States has adopted nationwide emission reduction targets and President Biden has reinstated the social cost

⁵¹ While FERC need not limit itself to significant new and changed circumstances, climate change and its impacts would certainly constitute significant new circumstances. In addition to the climate change impacts discussed in this sub-section, it is worth pointing out that the recently released Climate and Economic Justice Tool identifies the area surrounding this project as disadvantaged. *See* <https://screeningtool.geoplatform.gov/en/#10.07/25.939/-97.4076>.

⁵² IPCC, Climate Change 2022 Mitigation of Climate Change: Summary for Policy Makers SPM-4 (Feb. 2022), *available at* <https://www.ipcc.ch/report/sixth-assessment-report-working-group-ii/> (attached).

⁵³ *Id.* at SPM-32.

⁵⁴ *Id.* at SPM-36.

⁵⁵ 169 FERC ¶ 61,131 P109

⁵⁶ *Vecinos*, 6 F.4th at 1329.

of carbon protocol. FERC must reconsider the certificate in light of each of these developments.

We note that, with respect to climate change, the facts here are different than in other cases in which FERC has asked, in considering whether to extend a certificate, whether prior factual findings remained valid. In prior cases, FERC's initial certificate order and environmental review in fact evaluated the environmental impact at issue, including reaching a conclusion about significance, need for or appropriateness of mitigation, etc. *See, e.g., Arlington Storage Co.*, 155 FERC ¶ 61,165 P18. Here, in contrast, the issue is not whether FERC must reverse a prior conclusion, but instead whether FERC must now fill what FERC previously acknowledged was a gap in the analysis.

Now, the United States has joined the Glasgow Pact, which calls for net-zero emissions by 2050, and a 45% reduction in emissions by 2030—the type of target that FERC claimed was missing before.⁵⁷ The Intergovernmental Panel on Climate Change has explained that achieving these reductions requires eliminating or reducing fossil fuel use and moving to renewable energy as extensively and as quickly as possible.⁵⁸ Accordingly, Executive Order 14,008 instructs federal agencies to discourage “high carbon investments” or “intensive fossil fuel-based energy.”⁵⁹ Peer-reviewed published literature similarly affirms that every year of delay in phasing out fossil fuel infrastructure makes carbon “lock-in” more difficult to escape and the possibility of keeping global temperature rise below 1.5°C less likely.⁶⁰

As we've previously explained, an alternative to using overall emission reduction targets (or in addition), FERC can assess significance of greenhouse gas emissions using the social cost of carbon. Although this tool had been withdrawn, as a matter of federal policy, at the time FERC

⁵⁷ U.N. Framework Convention on Climate Change Secretariat, Glasgow Climate Pact at ¶17, available at https://unfccc.int/sites/default/files/resource/cop26_auv_2f_cover_decision.pdf and attached.

⁵⁸ Intergovernmental Panel on Climate Change, *Special Report: Global Warming of 1.5 C, Summary for Policymakers* at 15 (May 2019) (“IPCC 2019”), available at https://www.ipcc.ch/site/assets/uploads/sites/2/2019/05/SR15_SPM_version_report_LR.pdf and attached.

⁵⁹ Executive Order 14,008, 86 Fed. Reg. 7619, at § 102(f), (h) (Jan. 27, 2021).

⁶⁰ Smith, Christopher J. et al. 2019. Current fossil fuel infrastructure does not yet commit us to 1.5°C warming. Nature Communications. doi.org/10.1038/s41467-018-07999-w, attached.

reviewed and approved this project, it was formally readopted in early 2021,⁶¹ and in the past year, the Environmental Protection Agency has repeatedly called on FERC to use this readopted tool in the evaluation of individual natural gas infrastructure projects.⁶² While Protestors contend that the social cost of carbon has consistently been generally accepted in the scientific community, the fact that the protocol did not reflect official federal policy at the time FERC reviewed and approved this project, but that it does now, coupled with the fact that EPA has affirmed appropriateness of the tool for FERC's project specific reviews, are changed circumstances that demonstrate that FERC can fill what FERC previously recognized was a gap in the analysis.

2. FERC Must Revisit the Impact of this Project on Environmental Justice Communities

As FERC is already aware, its previous environmental justice analysis was inadequate. If FERC does not deny this extension outright, it must perform an adequate environmental justice analysis. Among other considerations, FERC must ensure that all relevant data is current to make sure that any relevant changes that have occurred in the project area since FERC's initial analysis are captured in the new analysis.

3. FERC Has Not Considered Impacts on Recently Listed Species

FERC must evaluate changed circumstances for two species recently listed under the Endangered Species Act ("ESA"): the endangered Rice's whale (formerly designated as the Gulf of Mexico population of the Bryde's whale)⁶³ and the threatened oceanic whitetip shark.⁶⁴

The Rice's whale was listed as an endangered species on August 23, 2021, well after the issuance of the underlying certificates here. The whale was previously considered a subpopulation of the Bryde's whale, and National Marine Fisheries Service's ("NMFS") response to FERC's

⁶¹ Executive Order 13,990, Protecting Public Health and the Environment and Restoring Science to Tackle the Climate Crisis, 86 Fed. Reg. 7037, 7040 (Jan. 25, 2021).

⁶² *E.g.*, EPA, Comment on Iroquois Gas Transmission System FEIS, CP20-48 (Dec. 20, 2021), Accession 20211220-5086.

⁶³ 86 Fed. Reg. 47,022 (Aug. 23, 2021).

⁶⁴ 83 Fed. Reg. 4,153 (Jan. 30, 2018).

request for consultation under ESA discussed impacts of the project on the Bryde's whale.⁶⁵ But NMFS and FERC must re-evaluate the project in light of new information about whale and the new listing. For example, NMFS concluded that the likelihood of a project-related vessel strike of a Bryde's whale was low, but now the Rice's whale has been recognized as a distinct species with only an estimated 51 living individuals,⁶⁶ making it one of the most endangered whales on earth. Thus, even if the likelihood of a ship strike has not increased relative to NMFS's previous analysis, new research suggests that consequences of a strike are more severe than previously recognized. For the Rice's whale to recover, it can only afford to lose one whale approximately every 15 years as a result of human activity. After, NMFS responded to FERC's request for consultation regarding this project, NMFS issued a biological opinion concluding that exploration and development of oil and gas in the Gulf of Mexico would likely jeopardize the continued existence of what was once called the Gulf of Mexico population of Bryde's whales, in which NMFS explained that because of the "precarious status [of the species], any effects that are expected to reduce the fitness of individuals or result in mortality are of great concern."⁶⁷

And, in addition to the increased severity of consequences, recent research suggests that the likelihood of impacts to a Rice's whale are also greater than previously recognized. For one, NMFS concluded that a strike was unlikely because the geographic range of the whale population was principally confined to the Florida coast and away from the routes that would primarily be used by LNG tankers associated with this project.⁶⁸ But the peer-reviewed research that led to identification of the Rice's whale as a distinct species indicates that Rice's whales may also be

⁶⁵ Accession No. 20190822-4001 at 14.

⁶⁶ NMFS, *Bryde's Whale*, Northern Gulf of Mexico Stock, NOAA Fisheries (April 2021), https://media.fisheries.noaa.gov/2021-07/f2020_AtlGmexSARs_GMexBrydes.pdf (attached).

⁶⁷ NMFS, Biological Opinion on the Federally Regulated Oil and Gas Program Activities in the Gulf of Mexico, FPR-2017-9234, 553 (Mar. 13, 2020) (emphasis added), *available at* <https://repository.library.noaa.gov/view/noaa/23738> (attached).

⁶⁸ Accession No. 20190822-4001 at 14-15.

present along the Texas coast.⁶⁹ Specifically, whales have been observed there,⁷⁰ and historic whaling data suggests that the whales used to be found in the western Gulf of Mexico.⁷¹ This may indicate that current habitat of the Rice's whale may extend beyond the area previously described by NMFS, or that a separate population of the Rice's whale exists near the Texas coast,⁷² in areas that may be impacted by this project.

In addition, NMFS did not address the impact of noise on the Rice's whale. One assertion by NMFS in its initial analysis was that vessel strikes were less likely because LNG vessels make more noise than other types of ships, which, according to NMFS, makes it easier for aquatic species to avoid LNG vessels.⁷³ But NMFS did not address the impact of noise itself on the Rice's whale. This silence contradicts previous statements made by NMFS—that noise can harm whales by “hindering their ability to use sound, causing a disruption of their ability to communicate, choose mates, find food, avoid predators, and navigate.”⁷⁴

FERC must also consider the impacts on the recently-listed whitetip shark. While the whitetip shark was listed before FERC and NMFS performed their initial analyses, neither addressed this species or explained its exclusion.

4. FERC Must Revisit the Economic and Upstream Impacts of the Project

Because the applicants delayed the project, and now seek an extension, because of changes in gas markets and because market demand for the project has been insignificant, FERC must evaluate the same as it reconsiders its certificate decisions. As noted above, FERC has already concluded that increases in LNG exports are driving large increases in domestic gas

⁶⁹ Rosel, P.E., Wilcox, L.A., Yamada, T.K., & Mullin, K.D. (2021). *A new species of baleen whale (Balaenoptera) from the Gulf of Mexico, with a review of its geographic distribution*. *Marine Mammal Science*. 37(2), 577-610. doi:10.1111/mms.12776 (attached).

⁷⁰ *Id.* at 588.

⁷¹ *Id.* at 597.

⁷² *Id.*

⁷³ Accession No. 20190822-4001 at 13.

⁷⁴ <https://www.fisheries.noaa.gov/species/brydes-whale> (attached).

prices.⁷⁵ To date, no federal agency has addressed whether this level of export-driven price increases is consistent with the public interest. This is likely because, as FERC is aware, exporting LNG in the contiguous United States is a relatively recent phenomenon.⁷⁶

Historically, the Department of Energy, rather than FERC, has held responsibility for evaluating the impact of export projects on domestic prices and supply, as the D.C. Circuit explained in *Sierra Club v. FERC*, 827 F.3d 36 (D.C. Cir. 2016) (“*Freeport*”). However, after FERC’s initial certificate decisions approving this project, DOE disclaimed authority over impacts occurring upstream of the point of export, and thus the predicate for *Freeport*, as part of a NEPA Categorical Exclusion.⁷⁷ Protestors contend that DOE’s interpretation of its own authority is mistaken, and that this categorical exclusion is unlawful. And we note that DOE has announced that it will reconsider this rule.⁷⁸ But FERC cannot simply assume that these issues will work themselves out, or that someone else will consider the issue. If DOE will not exercise authority over upstream impacts, FERC must.

Alternatively, even if DOE *does* consider the impact of the Rio Grande LNG project on gas prices and production, FERC must *also* integrate such evaluation into FERC’s NEPA analysis, pursuant to FERC’s statutory obligation to act as the “lead agency,” 15 U.S.C. § 717n(b)(1), and the requirement to ensure that NEPA review is not “segmented,” *Del. Riverkeeper v. FERC*, 753 F.3d 1304, 1313 (D.C. Cir. 2014). *Freeport*, in holding that FERC was not required to consider upstream impacts in that case, explicitly refrained from addressing FERC’s obligations as lead agency or the rule against segmentation.⁷⁹ But FERC must address those issues here.

⁷⁵ *Supra* note 32.

⁷⁶ See e.g., Jacob Gronholt-Pedersen, *U.S. exports first shale gas as LNG tanker sails from Sabine Pass terminal*, Reuters (Feb. 24, 2016), <https://www.reuters.com/article/us-shale-export/u-s-exports-first-shale-gas-as-lng-tanker-sails-from-sabine-pass-terminal-idUSKCN0VY08B>.

⁷⁷ DOE: Proposed Rule, NEPA Implementing Procedures, 85 Fed. Reg. 25,341 (May 1, 2020); *accord* Final Rule, 85 Fed. Reg. 78,198 (Dec. 4, 2020).

⁷⁸ <https://www.reginfo.gov/public/do/eAgendaSimpleSearch>.

⁷⁹ *Freeport*, 827 F.3d at 45.

5. FERC Must Use the Soon-to-be Reinstated NEPA Rules

If FERC does not deny the extension outright, it still must perform a supplemental a supplemental environmental analysis and issue a supplemental environmental impact statement that comprehensively assesses the environmental impacts of this project in light of significant changes that occurred since the initial approval, the disapproval of the environmental analysis underpinning the initial approval, and the various matters pending before FERC that relate to this project. In doing so, FERC must not use the NEPA regulations amended in September 2020: FERC can either use the regulations that were in effect when this project was first proposed, or apply the (substantially similar) NEPA regulations that the Council of Environmental Quality (“CEQ”) finalized on April 20, 2022.⁸⁰ The 2020 CEQ rules are arbitrary because, *inter alia*, they contravene the text of the NEPA statute in many regards, as argued in numerous lawsuits challenging the 2020 rules credited by CEQ⁸¹ and by CEQ itself in the regulatory preamble to the proposed rule.⁸² In accordance with the statutory text, CEQ proposes to again explicitly require consideration of indirect and cumulative effects,⁸³ and affirms that agencies can and must consider factors beyond the applicant’s goals when determining the purpose and need of the project.⁸⁴ Accordingly, to ensure compliance with the forthcoming NEPA regulations and to avoid violating the underlying statute, FERC’s NEPA analysis must conform to the once-and-present NEPA regulations, rather than those adopted in 2020.

* * *

The issue before FERC, in deciding whether to extend a certificate or instead to let it expire, is broader than just whether to prepare a supplemental NEPA document. The project will

⁸⁰ Council on Environmental Quality, 87 Fed. Reg. 23453.

⁸¹ *See* 86 Fed. Reg. at 55,758 (noting these lawsuits).

⁸² *E.g., id.* at 55,759.

⁸³ *Id.* at 55,763-65 (proposed 40 C.F.R. § 1508.1); *see also City of Davis v. Coleman*, 521 F.2d 661, 676-77 (9th Cir. 1975) (holding, prior to promulgation of CEQ regulations, that NEPA’s statutory text requires consideration of indirect effects), *Kleppe v. Sierra Club*, 427 U.S. 390, 409-10 (1976) (same, for cumulative effects).

⁸⁴ 86 Fed. Reg. at 55,760 (proposed 40 C.F.R. § 1502.13).

not proceed without an extension, and in deciding whether to extend these certificates, FERC must address whether the project continues to be in the public interest pursuant to the Natural Gas Act. Because those public interest determinations require balancing benefits of the project against harms, FERC cannot evaluate new information in isolation. Faced with new information regarding project harms, there is no way to consider this information other than to look to the project as a whole and ask whether the project provides benefits that justify these harms. And when faced with new information about mitigation—*i.e.*, ways in which the project could be modified to limit harms—FERC must evaluate whether to require such mitigation as a condition of extending the authorization.

III. Conclusion

Sierra Club hereby moves to intervene in this docket. The request for an extension must be denied, both because the applicants have not shown good cause for an extension and because factual developments following FERC's initial authorization call FERC's prior findings into question and demonstrate that the project is contrary to the public interest.

Respectfully submitted on April 27, 2022:

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CERTIFICATE OF SERVICE

I hereby certify that I have this day served the foregoing document upon each person designated on the official service list compiled by the Secretary in this proceeding.

Dated at Austin, TX on April 27, 2022.

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ARTICLE

A new species of baleen whale (*Balaenoptera*) from the Gulf of Mexico, with a review of its geographic distribution

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Abstract

Bryde's-like whales are a complex of medium-sized baleen whales that occur in tropical waters of all three major ocean basins. Currently, a single species of Bryde's whale, *Balaenoptera edeni* Anderson, 1879, is recognized, with two subspecies, Eden's whale, *B. edeni edeni* and Bryde's whale, *B. edeni brydei* (Olsen, 1913), although some authors have recognized these as separate species. Recently, a new, evolutionarily divergent lineage of Bryde's-like whale was identified based on genetic data and was found to be restricted primarily to the northern Gulf of Mexico (GOMx). Here, we provide the first morphological examination of a complete skull from these whales and identify diagnostic characters that distinguish it from the other medium-sized baleen whale taxa. In addition, we have increased the number of genetic samples of these Bryde's-like whales in the GOMx from 23 to 36 individuals, all of which matched the GOMx lineage. A review of Bryde's-like whale records in the Caribbean and greater Atlantic supports an isolated distribution for this unique lineage, augmenting the genetic and morphological body of evidence supporting the existence of an undescribed species of *Balaenoptera* from the Gulf of Mexico.

KEYWORDS

Balaenoptera, Bryde's whale, cetacean, Gulf of Mexico, species description, systematics, taxonomy

1 | INTRODUCTION

Despite being some of the largest animals on the planet and carrying the moniker of “charismatic megafauna,” it is always surprising to be reminded that the taxonomy and systematics of cetaceans, even today, remain in flux. Taylor, Perrin, et al. (2017) surveyed the extant cetacean fauna and concluded that of the currently recognized taxa, 32% have a high likelihood of underclassification errors and that an accurate taxonomy may contain twice the number of subspecies currently recognized. For example, two subspecies of killer whales (*Orcinus orca*) are currently recognized, but recent studies have suggested there are additional unrecognized subspecies or even species (Leduc et al., 2008). Taylor, Perrin, et al. (2017) concluded that the primary problems encountered when trying to address questions in cetacean taxonomy include the difficulty of obtaining skulls or obtaining tissue samples from elusive, often remote and difficult to sample taxa, coupled with the legal protections they are given. Due to these problems, studies often have inadequate numbers of samples, and/or an inadequate geographic sampling of these typically widely distributed species. As a result, robust taxonomic inference is often severely hindered.

Members of the “Bryde’s whale complex” in the genus *Balaenoptera* provide an excellent example of the historical and contemporary confusion that exists in cetacean taxonomy. These tropical and subtropical, and generally non-migratory whales, are found in all major ocean basins. They are difficult to distinguish visually based on external morphology and are therefore often collectively referred to as the “Bryde’s whale complex” or “Bryde’s-like whales.” Currently a single species of Bryde’s whale, *Balaenoptera edeni* Anderson, 1879, is recognized, with two recognized subspecies, Eden’s whale, *B. edeni edeni* and Bryde’s whale, *B. edeni brydei* (Olsen, 1913) (Committee on Taxonomy, 2019). These two subspecies have previously also been considered species based on morphological data (Soot-Ryen, 1961; Wada et al., 2003) and supported by genetic data (Rosel & Wilcox, 2014; Wada et al., 2003); see Rice (1998) for a historical review of differing opinions on the taxonomy of these whales. Genetic analysis of the type specimen for *B. edeni* has not yet been completed and a type specimen was not designated for *B. brydei* when it was named. As a result, despite the multiple lines of evidence for species-level differences, there has been a conservative treatment of the taxonomic rank of these two members and they are both currently recognized as subspecies of *B. edeni* (Committee on Taxonomy, 2019).

Balaenoptera edeni Anderson, 1879 was first described from a medium-sized balaenopterid whale that stranded in Myanmar in 1871 (Anderson, 1878 [1879]). They are thought to inhabit coastal waters of the Indian Ocean and the western Pacific, with genetically confirmed records from the East and South China seas and coastal waters throughout the northern Indian Ocean from Oman east to Indonesia (Jayasankar et al., 2009; Kershaw et al., 2013; Kim et al., 2018; Li et al., 2019; Rosel & Wilcox, 2014; Sasaki et al., 2006; Wada et al., 2003; Yoshida & Kato, 1999; Yusmalinda et al., 2017). To date there are no records from the Atlantic basin or the eastern Pacific. *B. brydei* Olsen, 1913 was described based on whales taken by the whaling industry in Saldanha Bay, South Africa (Olsen, 1913). These whales are generally associated with deeper, more pelagic waters and have a much broader worldwide distribution, with genetically confirmed records from the Atlantic, Pacific, and Indian Ocean basins (Alves et al., 2010; Herath, 2007; Kanda et al., 2007; Kershaw et al., 2013; Kim et al., 2018; Luksenburg et al., 2015; Murakami et al., 2018; Pastene et al., 2015; Penry, 2010; Penry et al., 2018; Rosel & Wilcox, 2014; Sasaki et al., 2006; Wada et al., 2003; Yoshida & Kato, 1999).

As recently as 2003, a new species of Bryde’s-like whale was removed from the complex when Wada et al. (2003) described a smaller balaenopterid, Omura’s whale, *Balaenoptera omurai*. The authors suggested, based on morphological comparisons of the skull, that *B. omurai* and the two *B. edeni* subspecies each have diagnostic features in the morphology of the vertex of the skull, and that all three should be considered distinct species: *B. omurai*, *B. edeni*, and *B. brydei*. Genetic analyses based on mitochondrial DNA (mtDNA) control region sequence data were consistent with the morphological distinctiveness of all three taxa, returning well-supported, reciprocally monophyletic groupings of the currently recognized *B. omurai*, *B. e. edeni*, and *B. e. brydei* (Kershaw et al., 2013; Rosel & Wilcox, 2014; Sasaki et al., 2006). Interestingly, while originally thought to be restricted to the western Pacific and the tropical eastern Indian oceans (Cerchio et al., 2019; Yamada, 2009), Omura’s whales have now been recorded

from the western and central Indian Ocean (Cerchio et al., 2015, 2019), and from the eastern and western tropical Atlantic Ocean, near and south of the equator (Cypriano Souza et al., 2017; Jung et al., 2016), indicating that the confusion in distinguishing amongst members of this closely related group of whales in the field has dramatically impaired understanding of each member's taxonomy, genetics, and distribution. Cerchio et al. (2019) provide a comprehensive review of the distribution of this species.

Most recently, Rosel and Wilcox (2014) identified a new, evolutionarily distinct lineage of Bryde's-like whales in the Gulf of Mexico (GOMx) (Figure 1). The presence of Bryde's whales in the GOMx was first recognized in 1965 (Rice, 1965) based on a whale that stranded alive on April 2, 1965 in the panhandle of Florida and was later towed to sea. Historically, these whales were assumed to be a population of the broadly distributed *B. edeni* species. Analysis of mitochondrial DNA (mtDNA) control region sequences of whales sampled in the northeastern GOMx revealed that this population is evolutionarily distinct from all other whales within the Bryde's whale complex and all other known balaenopterid species (Rosel & Wilcox, 2014). Phylogenetic analyses placed these GOMx whales on a strongly supported lineage separated from *B. e. edeni* and *B. e. brydei* sampled in the Atlantic, Pacific, and Indian Oceans (Rosel & Wilcox, 2014). Within the first 375 base pairs of the mtDNA control region, the whales from the GOMx exhibited 25 fixed differences differentiating them from *B. e. edeni* and *B. e. brydei* (Rosel & Wilcox, 2014). This number of fixed differences is two to three times greater than that observed between recognized right whale species (*Eubalaena* spp.) and is of the same magnitude as the number of fixed differences found between fin (*B. physalus*) and blue (*B. musculus*) whales over the same gene region (Rosel et al., 2017). For further comparison, Archer et al. (2013) found only two fixed differences between the fin whale subspecies in the North Atlantic and North Pacific.

Rosel and Wilcox (2014) recommended that, based on the significant number of diagnostic differences and the finding of reciprocal monophyly, the whales in the GOMx should be given taxonomic status equivalent to the currently recognized subspecies, but they did not provide a species description. This omission was due largely to the lack of an intact specimen to represent the holotype for the new taxon. In addition, criteria for recognizing species and subspecies of cetaceans based on mtDNA sequence data were also lacking at the time.



FIGURE 1 Aerial photograph of a Bryde's-like whale in the northeastern Gulf of Mexico. Photo credit: NMFS SEFSC and NEFSC under MMPA permit.

In January 2019, an adult male Bryde's-like whale stranded and died in the Everglades on the southwestern coast of Florida in the GOMx (field number FMMSN1908). The entire specimen was collected, and the intact skull and skeleton were deposited into the Smithsonian National Museum of Natural History collection (USNM 594665). In addition, Taylor, Archer, et al. (2017) described new guidelines and thresholds for delimiting cetacean subspecies and species using mtDNA control region sequence data. Here we reexamine the genetic distinctiveness of the Bryde's-like whales in the GOMx, adding data from new samples collected since the initial publication of Rosel and Wilcox (2014), new DNA sequence data available from recent publications on Bryde's whales worldwide, and in light of the guidelines and thresholds provided in Taylor, Archer, et al. (2017). We also provide a description of the morphological characteristics of the new specimen. The joint genetic and morphological data provide strong support for a new species of *Balaenoptera*.

2 | METHODS

2.1 | Genetic data

Rosel and Wilcox (2014) sequenced the complete mtDNA control region from 18 Bryde's-like whales remotely biopsied in the northeastern Gulf of Mexico (GOMx), three whales that stranded in the GOMx and two that stranded on the U.S. east coast. Here we add new DNA sequence data from 18 new skin samples collected between 2012 and 2019: 14 biopsy samples collected in the northeastern GOMx, the first biopsy sample ever collected in the western GOMx off Texas, and skin collected from two whales that stranded in Louisiana and a whale that stranded in Flamingo, Florida Bay, Everglades National Park. DNA was extracted using a standard proteinase K digestion followed by organic extraction (Rosel & Block, 1996) or a Qiagen DNeasy Blood and Tissue Kit following the manufacturer's instructions. DNA quality and quantity were assessed through gel electrophoresis and fluorometry, respectively. The complete mtDNA control region was amplified and sequenced in two overlapping fragments and the sex of each biopsy was genetically determined as described in Rosel and Wilcox (2014). Control region PCR products were purified via low melting point agarose gel extraction followed by agarose digestion or purified enzymatically using Exonuclease I and FastAP Thermosensitive Alkaline Phosphatase (Thermo Scientific). All PCR products were sequenced in both directions using the Applied Biosystems BigDye Terminator v1.1 cycle sequencing kit and run on an ABI 3130 or ABI 3500 Genetic Analyzer or sequenced commercially using a BigDye Terminator v3.1 cycle sequencing kit (Eurofins MWG Operon) on an ABI 3730xl Genetic Analyzer. Forward and reverse reads were independently edited using Sequencher v5.4.6 (GeneCodes) or Geneious Prime 2020.0.5 (<https://www.geneious.com>) and a final consensus sequence for each sample was assembled.

In an effort to locate a specimen that could serve as a holotype, we found a specimen at the Louisiana State University Museum of Natural History (LSUMZ 17027) that had been collected in 1954 and identified as a possible Bryde's whale (Lowery, 1974). To verify the species, we extracted and sequenced DNA from the specimen. A section of one occipital condyle was cleaned with 5% bleach solution and rinsed with distilled water, and surface bone removed by drilling with a sterile 3 mm drill bit. The drill bit was exchanged for a new sterile bit and bone powder then collected from within the condyle bone. DNA extraction was performed in an ancient DNA only laboratory where all surfaces and laboratory equipment were cleaned with 10% bleach prior to performing the extraction. DNA was extracted from 50 mg of bone powder using the Qiagen QIAamp DNA Investigator Kit after demineralization of the powder in 950 μ l of 0.5 M EDTA (pH 8.0) at room temperature for 18 hr. Extraction was performed according to the manufacturer's protocol for isolation of DNA from bone with the following adjustments: Buffer ATL was decreased from 360 μ l to 330 μ l, Buffer AL with carrier RNA was increased from 300 μ l to 700 μ l, and the ethanol added prior to binding to the QIAamp MinElute column was increased from 150 μ l to 350 μ l. A negative DNA extraction control was simultaneously run using 950 μ l of 0.5 M EDTA (pH 8.0).

For this bone sample, the 5' end of the mtDNA control region was amplified and sequenced using five overlapping fragments ranging from 132 to 160 base pair (bp) in length. The following sets of primer pairs were used to obtain control region sequence: L15874 (Vollmer et al., 2011) and Bede143R (5'-ATTAATTAAGTTATAGGAAGGT-3') annealing temperature $T_a = 50^\circ\text{C}$; Bede121F (5'-CTTGTCTTATACATATTATT-3') and Bede229R (5'-CTTCAACTGCTCGTGGT-3') $T_a = 50^\circ\text{C}$; Bede218F (5'-TGCTATGTATAACTGTGCATTC-3') and Bede310R (5'-GACTGGGAATGCATAACAG-3') $T_a = 45^\circ\text{C}$; BedeShort145F (5'-ACCACGAGCAGTTGAAGTCC-3') and BedeShort145R (5'-TCGTGATCTAATGGAGCGGC-3') $T_a = 55^\circ\text{C}$; BedeShort89F (5'-TGCTGTTATGCATTCCTCCAGT-3') and H16265 (Rosel et al., 1999) $T_a = 50^\circ\text{C}$. Each PCR was performed in a 50 μl reaction with 20 mM Tris-HCl (pH 8.4), 50 mM KCl, 1.5 mM MgCl_2 , 150 μM dNTPs, 2.5 U *Taq* DNA Polymerase (Invitrogen), 0.12 mg/ml BSA, 0.3 μM of each primer and 4–5 μl of DNA. The PCR profile included an initial denaturation step of 95°C for 30 s followed by 45 cycles of 95°C for 30 s, T_a as listed above for 30 s, and 72°C for 30 s with a final extension at 72°C for 7 min. PCR products were purified using Exonuclease I and FastAP Thermosensitive Alkaline Phosphatase (Thermo Scientific) and sequenced in both directions using the Applied Biosystems BigDye Terminator v1.1 cycle sequencing kit on an ABI 3130 Genetic Analyzer. Forward and reverse reads were independently edited using Geneious Prime 2020.0.5 and consensus sequences for each fragment were created then assembled to create one continuous sequence of the 5' end of the control region. The final sequence was compared to the control region haplotypes of baleen whales recovered in the GOMx and western North Atlantic.

The Bayesian phylogenetic analysis presented in Rosel and Wilcox (2014) was repeated with the addition of the new sequences described above and augmented with new sequences from the other Bryde's whale taxa published since 2014 and available in GenBank. The additional published sequences expanded the geographic range of the original phylogenetic analysis to include localities of Bryde's whales, *B. e. brydei*, in the southern Caribbean (Luksenburg et al., 2015), the East China Sea (Kim et al., 2018), the California coast of the eastern North Pacific,¹ off the coast of Chile in the eastern South Pacific (Pastene et al., 2015) and the coast of Brazil in the western South Atlantic (Pastene et al., 2015). The geographic range of Eden's whale, *B. e. edeni*, was increased by including new sequences from stranded whales in Bali, Indonesia in the eastern Indian Ocean (Yusmalinda et al., 2017) and the South China Sea (Li et al., 2019). Because the published sequences available in GenBank are of varying lengths, we performed the phylogenetic analysis on three different control region alignments: a 305 bp alignment that allowed us to include the broadest geographic coverage of the Bryde's whale complex contained 73 haplotypes, a 375 bp alignment containing 22 haplotypes and finally a 721 bp alignment containing 11 haplotypes. The latter alignment still allowed for coverage of all members of the Bryde's whale complex and geographic coverage from the North Atlantic (including the GOMx and Caribbean Sea), South Atlantic, North Pacific (including the East and South China Seas), and the South Pacific. The alignments also included haplotypes from *B. omurai* and from other balaenopterid whales, while *Eubalaena glacialis* served as the outgroup (Table S1). All sequences were aligned using MUSCLE v3.8.425 and default parameters in Geneious Prime 2020.0.5.

Phylogenetic analyses were performed on each alignment using MrBayes v3.2.6 (Huelsenbeck & Ronquist, 2001). First, jModeltest v2.1.6 (Posada, 2008) and the Bayesian information criterion (BIC) were used to determine the best model given the control region alignments; TPMuf+G for the 305 and 375 bp alignments and TPM3uf + I + G for the 721 bp alignment. As a result, the more parameterized general time reversible (GTR) model with appropriate corrections (gamma and/or invariable sites) was used. For each alignment, MrBayes was run in Geneious Prime 2020.0.5. Bayesian searches used four chains, two runs, and 5,000,000 generations using default priors in MrBayes. Burn-in was set to 25%. Convergence of the runs was determined by examining the average standard deviation of split frequencies and using Tracer v1.5 (Rambaut & Drummond, 2007).

A characteristic attributes (CAs) diagnosis (Davis & Nixon, 1992; Lowenstein et al., 2009; Sarkar et al., 2002) was performed using the control region sequences of *B. e. edeni*, *B. e. brydei*, *B. omurai*, and the haplotypes from the GOMx whales for the 305 bp control region alignment using all sequences available in GenBank. While it is the shortest alignment, the 305 bp region allows us to include the greatest number of haplotypes for all taxa involved,

thereby improving the likelihood that identified diagnostic sites reflect true interspecific differences and not simply intraspecific variability.

Subsequent to the identification of this unique lineage of whales in the GOMx in 2014, standards and guidelines for delimiting cetacean species and subspecies based on mtDNA control region sequences were established by Taylor, Archer, et al. (2017). Rosel et al. (2017) surveyed levels of genetic divergence in the mtDNA control region between accepted pairs of species, subspecies, and populations of cetaceans, and explored the efficacy of different metrics of genetic divergence for correctly identifying these different taxonomic levels. They found that the genetic measure of net nucleotide divergence or d_A (Nei, 1987) performed well at distinguishing species from subspecies and populations. This metric provides a measure of number of net nucleotide substitutions or net divergence between two groups, accounting for the level of within group variability. Taylor, Archer, et al. (2017) built on these results, recommending quantitative standards for delimiting new species and subspecies based on d_A coupled with a measure of diagnosability (defined as “a measure of the ability to correctly determine the taxon of a specimen of unknown origin based on a set of distinguishing characteristics” by Archer et al., 2017). If $d_A > 0.02$ between two groups of cetaceans, those groups exceed the threshold of net nucleotide divergence consistent with species level differences and could warrant species status when also coupled with a diagnosability of at or near 100%. In cases where $0.004 < d_A < 0.02$ between two taxonomic groups, those groups exhibit levels of genetic divergence consistent with subspecies. To place the degree of divergence of the Bryde's-like whales from the GOMx into this context, we estimated net nucleotide divergence, d_A (Nei, 1987), for both Bryde's whale subspecies, Omura's whale, and sei whale, *B. borealis*, sequences of the 375 bp alignment using MEGA X: Molecular Evolutionary Genetics Analysis across computing platforms (Kumar et al., 2018; Stecher et al., 2020). For one haplotype, information on the number of individuals with the haplotype was not provided in the publication and was therefore assigned as a single individual. Fixed differences were calculated using DNAsp v6.12.03 and fixed indels determined by viewing the alignments in Geneious Prime 2020.0.5.

All of the new samples except for the bone sample (LSUMZ 17027) were genotyped at the 17 microsatellite loci identified as polymorphic in Rosel and Wilcox (2014) using a Qiagen Type-it Microsatellite PCR kit and the manufacturer's protocols. The loci used were: GATA028, GATA053, GATA098, GATA417, GGAA520 (Palsbøll et al., 1997), AC137, CA234, GT023, GT122, GT307, GT541 (Bérubé et al., 2005), EV104 (Valsecchi & Amos, 1996), Ppho130, Ppho137 (Rosel et al., 1999), SW13 (Richard et al., 1996), GM199/200, GM417/418 (Amos et al., 1993). Reverse primers for all loci except GATA028, GATA053, GT023 and Ppho137 were pigtailed following Brownstein et al. (1996). Multiplexing allowed all 17 loci to be genotyped in three PCR reactions (Table S2). All PCR reactions included positive and negative no-DNA controls. Resultant PCR products, including all controls, were genotyped on an ABI 3130 or an ABI 3500 Genetic Analyzer using Genescan 500 LIZ or Genescan 600 LIZ v2.0 dye size standard (Applied Biosystems), respectively. The raw data were scored using GeneMapper v6 (Life Technologies/Applied Biosystems). Observed and expected heterozygosities and the number of alleles per locus were calculated using Arlequin v3.5 (Excoffier & Lischer, 2010). To identify whether multiple biopsies were collected from the same animals, we used Microsatellite Toolkit (Park, 2001) to search for individuals with identical multilocus genotypes and we estimated probability of identity $P_{(ID)}$ and the more conservative $P_{(ID)_{sib}}$ (Waits et al., 2001) using GenAIEx v6.5 (Peakall & Smouse, 2006). Samples identified as having identical genotypes were also checked to see that they had the same sex and the same control region sequence.

2.2 | Morphological data

On January 29, 2019, a 1,126 cm adult male Bryde's-like whale (FMMSN1908) stranded in Flamingo, Florida Bay, Everglades National Park, on the southwestern coast of the Florida Peninsula in the GOMx. The Florida Fish and Wildlife Conservation Commission (FWC)-Southwest Field Laboratory coordinated with NOAA National Marine Fisheries Service, Southeast Fisheries Science Center, and volunteers from multiple agencies to salvage the carcass

for full necropsy and preservation. A suite of external observations was taken by the stranding responders and the carcass was then buried in Fort De Soto Park, Florida. In October 2019, after being moved from Florida to North Carolina for further cleaning, the entire skeleton was exhumed, cleaned further, and deposited in the U.S. Museum of Natural History at the Smithsonian Institution (USNM 594665). We took 10 measurements of the skull (Table 1) to the closest millimeter using a calipers and photographed the skull. In addition, we examined and compared the characteristics of the vertex of the skull identified by Wada et al. (2003) as important for distinguishing among the different Bryde's whale taxa, including Omura's whale. These include the shape and extent of the ascending process of the posterior end of the maxilla, the extent to which the frontals are exposed, the extension of the premaxilla and whether it reaches the frontal, and whether the alisphenoid and squamosal bones are in contact. We also directly compared these features between this whale (USNM 594665) and USNM 572922, a subadult male that stranded on the North Carolina coast in 2003 that has been genetically confirmed to belong to the lineage that identifies the Bryde's-like whales in the GOMx (Rosel & Wilcox, 2014).

2.3 | Distributional data

The National Marine Fisheries Service (NMFS), Southeast Fisheries Science Center (SEFSC) has conducted marine mammal vessel and aerial surveys in the northern GOMx, covering nearshore, continental shelf and slope, and oceanic waters out to the U.S. EEZ since the late 1980s. We reviewed and compiled all "Bryde's whale," "*Balaenoptera* sp.," and "Bryde's/sei whale" sightings from these GOMx surveys spanning 1989–2019. We similarly compiled and reviewed all NMFS marine mammal vessel and aerial surveys in the U.S. EEZ of the Atlantic coast between 1992 and 2019. Depths at each visual sighting location were extracted using ArcGIS and the ETOPO2 2-arc-minute gridded global relief data set.

We also reviewed 13 sightings records provided by the Bureau of Ocean Energy Management (BOEM) made by protected species observers (PSO) on seismic vessels in the GOMx from 2010 to 2014 as part of the required mitigation measures. These observers record time, location, distance to vessel, water depth, species, a visual description of the whale, and additional sighting details for each sighting. As other whales are present in the GOMx, including sperm whales and beaked whales (Family Ziphiidae), which, at a distance, could potentially be confused with a baleen whale, we evaluated each sighting description to determine the likelihood the sighting was of a Bryde's-like whale.

Finally, we reviewed stranding data from the U.S. GOMx coast and the U.S. Atlantic seaboard for those strandings listed as "Bryde's whales" through query of the NOAA National Marine Mammal Health and Stranding Response Database and the Division of Mammals Collections at the Smithsonian National Museum of Natural History (USNM), including examination of all written records in the USNM archive. While stranding data can potentially

TABLE 1 Ten measurements of the skull of USNM 594665 (holotype).

Measurement	Length (cm)	Comments
Condylbasal length	284.4	right side as left premaxilla is broken
Maxillary length	204.5	right side as left premaxilla is broken
Zygomatic width	142.6	
Exoccipital width	101.6	
Occipital condyle width	25.1	
Rostrum width at antorbital notch	86.7	
Maximum nasal width	18.8	
Maximum nasal length	32.9	right side
Occipital shield length	63.6	straight/parallel measurement

provide some information on cetacean distribution, it is important to recognize that stranding location may not always represent habitat or area of origin due to currents and winds moving carcasses away from normal distribution. We also reviewed the published literature for both regions and broadened the search to cover the entire Atlantic Ocean to further evaluate the distribution of Bryde's whale taxa in the Atlantic Basin.

3 | RESULTS

3.1 | Genetic data

The full mtDNA control region (936 bp) was successfully sequenced for 15 new remote skin biopsy samples and three strandings. No new haplotypes were found; all new animals exhibited the most common haplotype (Bede001, GenBank accession KJ586818). The 5' end of the mtDNA control region (381 bp) that was sequenced for bone sample LSUMZ 17027 also matched the Bede001 haplotype. In combination with those samples presented in Rosel and Wilcox (2014), a total of 42 whale tissue samples (35 biopsies, seven strandings) have been analyzed from the GOMx and two strandings from the Atlantic.

All tissue samples were successfully genotyped at the 17 microsatellite loci. Only a single new allele was found at locus GATA098, despite increasing the overall genotyped sample size by 59%. Probabilities of identity ($P_{ID} = 1.50 \times 10^{-4}$; $P_{ID(sib)} = 1.36 \times 10^{-2}$) were relatively high due to the low heterozygosity exhibited by all the loci (Table S2). Microsatellite Toolkit identified eight duplicate samples across the pooled old and new sample set, with several animals biopsied eight to nine years apart. After removing duplicate samples, and including the LSU specimen, the total number of individual whales sampled in the northern GOMx and the two strandings on the east coast between 1954 and 2019 is 36. The sex ratio across these unique individuals (biopsies and strandings) is 19F:15M; the sex of two stranded animals could not be determined.

The Bayesian analyses based on the mtDNA control region alignments revealed the same pattern found previously (Rosel & Wilcox, 2014). *B. e. edeni*, *B. e. brydei*, and the Bryde's-like whales in the GOMx are each reciprocally monophyletic with posterior probabilities of 0.99 to 1.0 (Figures 2, S1, S2). The characteristic attributes diagnosis on the 305 bp control region alignment identified a total of 30 diagnostic sites that distinguish among *B. e. brydei*, *B. e. edeni*, *B. omurai*, and the Bryde's-like whales from the GOMx (Table 2). These include 24 of the 25 diagnostic sites reported in Rosel and Wilcox (2014) and five additional sites previously described in Cypriano Souza et al. (2017). Nucleotide position 15682 was counted in error in Rosel and Wilcox (2014) as a diagnostic position. A novel diagnostic site for the Bryde's-like whales from the GOMx not previously noted (position 15564) was identified due to removal of one *B. e. brydei* haplotype (GenBank accession EF068039) due to sequencing error reported by the authors (L. Pastene, personal communication, February 2020). The total number of diagnostic positions for each of the four taxa was: *B. e. edeni* ($n = 2$), *B. e. brydei* ($n = 3$), *B. omurai* ($n = 16$), and Bryde's-like whales from the GOMx ($n = 10$). Nei's net nucleotide divergence, d_A , between the whales from the GOMx and the two *B. edeni* subspecies based on the 375 bp alignment ranged from 0.103 to 0.128 (Table 3), significantly greater than the minimum value of 0.02 for species level distinction identified by Taylor, Archer, et al. (2017). The number of fixed differences likewise remains high between the whales from the GOMx and those elsewhere (Table 3) and provide 100% diagnosability based on this gene region.

3.2 | Morphological data

The whale that stranded in January 2019 was an adult male (Figure 3). Total length was 1,126 cm. The whale was a uniform dark gray on the dorsal side with a large falcate dorsal fin; the flippers were uniformly dark. The ventral side was lighter in coloration, particularly on the ventral side of the peduncle. The ventral side of the tail was lighter in

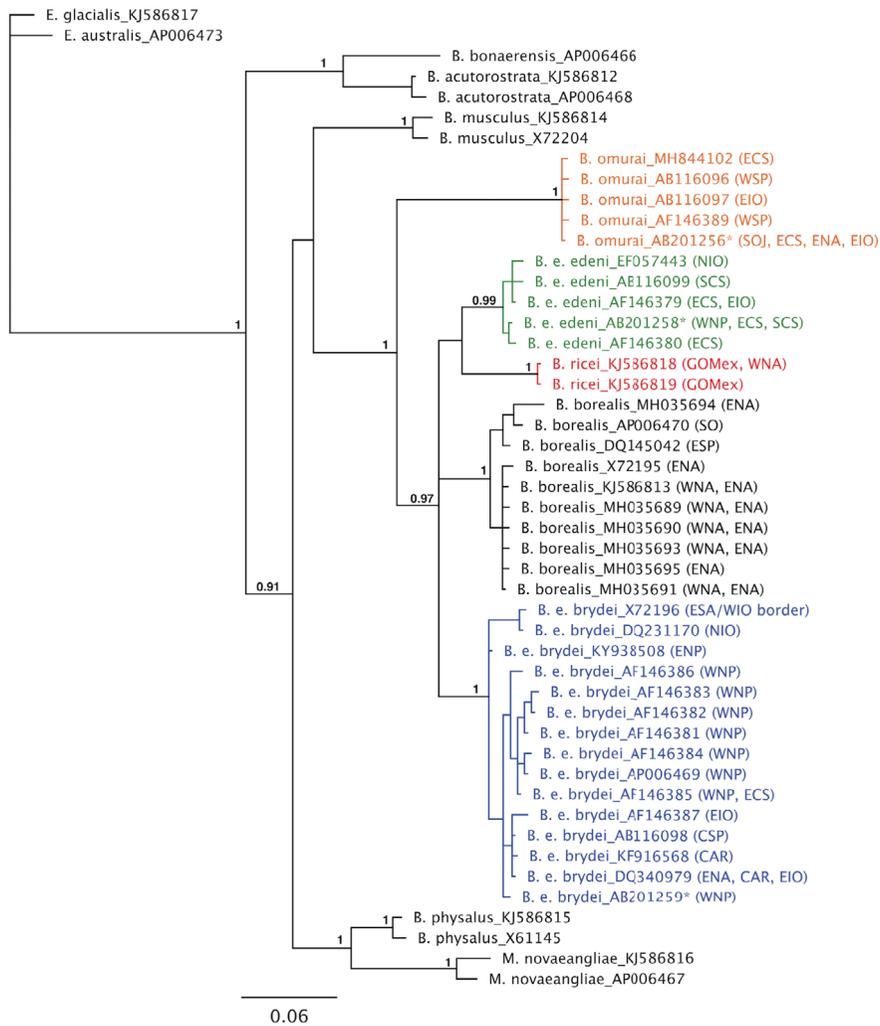


FIGURE 2 Bayesian reconstruction of phylogenetic relationships among members of the Bryde's whale complex based on 375 bp control region alignment. Posterior probabilities >0.90 are shown at nodes. Haplotypes with an asterisk indicate individuals morphologically identified to species by Sasaki et al. (2006) and used to identify the species clades. Length of scale bar is proportional to the number of nucleotide substitutions per site. GenBank accession numbers as well as geographic localities where the haplotype has been recorded are included in haplotype labels (Atlantic Ocean: WNA = western North Atlantic, ENA = eastern North Atlantic, ESA = eastern South Atlantic, GOMex = Gulf of Mexico, CAR = Caribbean Sea; Pacific Ocean: WNP = western North Pacific, ENP = eastern North Pacific, WSP = western South Pacific, ESP = eastern South Pacific, CSP = central South Pacific, ECS = East China Sea, SCS = South China Sea, SOJ = Sea of Japan; Indian Ocean: NIO = northern Indian Ocean, WIO = western Indian Ocean, EIO = eastern Indian Ocean; Southern Ocean: SO). See Table S1 for all sequences that were collapsed to each haplotype.

color, particularly towards the middle and at the peduncle. Three ventral pleats extended past the umbilicus at the midline. The pleats were counted from the right lateral aspect to the mid-line; in line with the flipper insertion, 27 pleats were counted, given a total count of 54 pleats. As is typical for all Bryde's-like whales, three ridges were present on the rostrum.

TABLE 2 Characteristic attributes (CAs) analysis of the control region (305 bp) for Bryde's-like whales and Omura's whale identifying 30 diagnostic sites. *n*: total number of individuals used in the analysis for each taxon. Grayed cells identify sites diagnostic for a species. Nucleotide positions 15536–15818 correspond to the *B. e. brydei* mtDNA genome of GenBank accession number AB201259.

	15536	15554	15556	15563	15564	15565	15569	15573	15574	15575	15578	15585	15588	15592	15605	15608	15609	15613	15616	15621	15623	15624	15660	15671	15672	15735	15756	15769	15816	15818
<i>B. e. brydei</i> (<i>n</i> = 629)	C	A	T	T	T	T	C	T	A	T	A	C	A	T	T	C	T	G	G	A	A	T	T	G	C	A	C	A	C	C
<i>B. e. edeni</i> (<i>n</i> = 67)	*	*	C	*	*	*	*	*	*	*	*	*	*	C	*	C	*	*	T	*	*	*	*	*	*	*	*	*	*	*
GONX whales (<i>n</i> = 36)	*	*	*	C	*	*	*	*	*	*	T	*	*	*	*	T	C	*	T	*	*	G	C	*	*	G	T	C	T	G
<i>B. omururai</i> (<i>n</i> = 41)	T	G	C	*	*	C	T	C	T	C	G	*	G	*	C	*	C	A	T	G	*	*	C	T	A	*	*	T	*	*

TABLE 3 Genetic divergence estimates for Bryde's-like, sei, and Omura's whales based on the 375 bp alignment of the mitochondrial DNA control region. Number of individuals (*n*), number of haplotypes (*h*). Net between group divergence (d_A , Nei 1987) corrected using the T3P model is below diagonal, within group divergence is along diagonal, and number of fixed differences (number of indels) between taxa above the diagonal.

	<i>n</i>	<i>h</i>	GOMx whales	<i>B. e. edeni</i>	<i>B. e. brydei</i>	<i>B. borealis</i>	<i>B. omurai</i>
GOMx whales	36	2	0	25	24	22 (1)	51 (8)
<i>B. e. edeni</i>	22	5	0.103	0.009	20	20 (1)	42 (8)
<i>B. e. brydei</i>	27	15	0.128	0.102	0.019	17 (1)	39 (5)
<i>B. borealis</i>	90	10	0.114	0.102	0.083	0.016	41 (9)
<i>B. omurai</i>	17	5	0.304	0.229	0.246	0.264	0.004

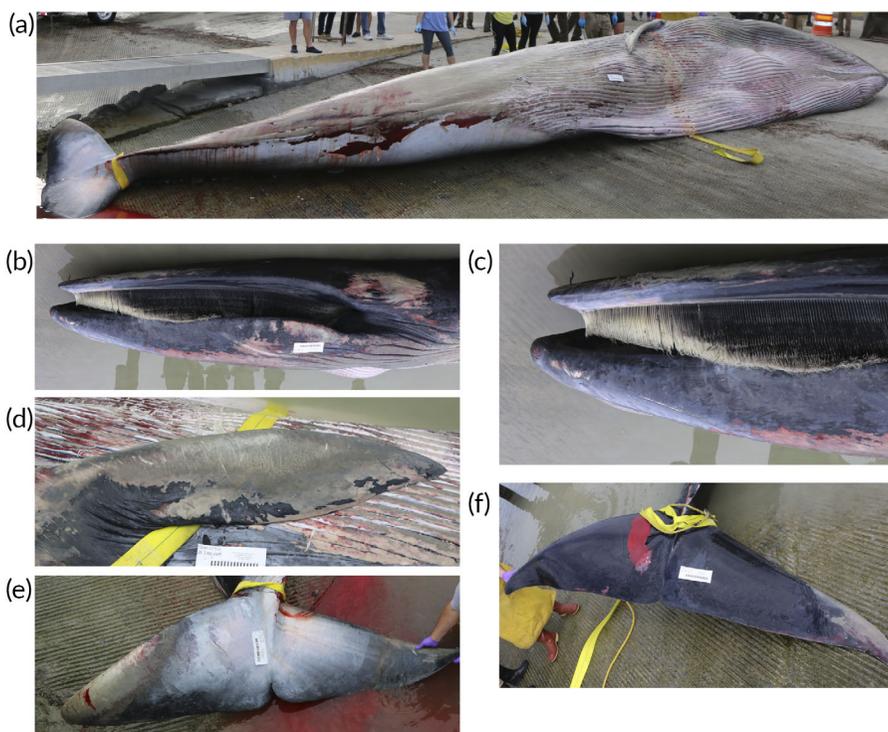


FIGURE 3 Images from the whale that stranded January 2019 in the Gulf of Mexico (holotype specimen USNM 594665, FMMSN1908). (a) ventral view of body; (b, c) right rack of baleen and close-up of anterior portion of the rack; (d) right flipper; (e) ventral and (f) dorsal view of the fluke. Scale bar is 10 cm. Photos in 3b and 3c were inverted so the dorsal side is up. Photo credit: Florida Fish and Wildlife Conservation Commission.

Wada et al. (2003), Yamada et al. (2006), and Yamada et al. (2008) utilized several diagnostic characteristics of the skull to distinguish between *B. e. edeni*, *B. e. brydei*, and *B. omurai*. Omura's whales exhibit the most differences, including two foramina on the parieto-squamosal suture. *B. e. edeni* is unique in the shape of the ascending process of the maxilla (slender and round) and in the broadly exposed frontal bones and the “pedestal” they form for the ascending process of the maxilla (Wada et al., 2003). We utilized the diagnostic characters indicated by Wada et al. (2003), Yamada et al. (2006); Yamada et al. (2008) to examine the skull of the 2019 stranded whale (USNM 594665). The foramina seen in Omura's whale were not present in the 2019 stranded whale (USNM 594665). The

Bryde's-like whales from the GOMx are further distinguished from *B. omurai* by the posterior end of the premaxillae, which reach the frontals in the GOMx whales but not in *B. omurai*. In the GOMx whales, the frontals are only narrowly exposed, forming a thin, narrow belt, clearly distinguishing them from *B. e. edeni*. In these characteristics of the vertex of the skull, the GOMx whales are most similar to *B. e. brydei*. However, we identified several characteristics in the vertex consistent in both the 2019 specimen (USNM 594665) and the immature whale specimen collected in North Carolina (USNM 572922) that are unique to the Bryde's-like whales from the GOMx and can be used to separate them from the other Bryde's whale subspecies and from *B. omurai*. We observed that the anterior portion of the frontal bones wraps around the posterior end of the nasals and protrudes on their medial side to separate the posterior end of the nasals. In addition, the posterior end of the nasals curves laterally and has relatively smooth margins, while in *B. e. brydei* the posterior end of the nasals remains straight and has somewhat crenulated margins.

3.3 | Distributional data

3.3.1 | Gulf of Mexico

Compilation of 181 visual sightings from NMFS marine mammal aerial and vessel surveys between 1989 and 2019 indicates these whales primarily have a restricted distribution along the continental shelf break near the De Soto Canyon area of the northeastern GOMx (Figure 4). The water depths of visual sightings ranged from 117 m to 408 m with all but two in the range of 151–352 m. In addition, a whale tagged in this area in October 2010 was satellite-tracked for a month, during which time the animal remained in waters between 100 and 400 m depth within the northeastern GOMx (Soldevilla et al., 2017).

During this survey period (1989–2019), two of the 181 sightings were of a large baleen whale (recorded as *Balaenoptera* sp. or Bryde's/sei whale) in the western GOMx west of the Mississippi River delta in waters <300 m deep, but neither could be identified to species. However, in August 2017, the first confirmed sighting of a live Bryde's-like whale in the western GOMx was made during a NMFS vessel survey (National Marine Fisheries Service, 2018). This whale was seen off the Texas coast in 225 m water depth. Analysis of the mtDNA control region from a skin biopsy sample collected from the whale confirmed that it belongs to the lineage unique to Bryde's-like whales from the GOMx. Finally, acoustic moorings placed in the western GOMx south of Louisiana have recorded some unique vocalizations thought to belong to Bryde's-like whales from the GOMx (M. Soldevilla, personal communication, July 2019). Both the recordings and the sighting in the western GOMx were in water depths similar to the habitat used by the whales in the northeastern GOMx.

Examination of 13 sightings provided by BOEM from marine mammal observers on seismic vessels provided only minimal insight. No sightings were close enough for observers to record whether the diagnostic lateral ridges on the dorsal surface of the head were visible and thus none could unequivocally be identified as a Bryde's-like whale. Five sightings were in water depths >1,000 m, which is inconsistent with the Bryde's-like whales in the GOMx, and several of these observations described surfacing followed by multiple blows, a behavior more consistent with sperm whales recovering after a deep dive. These five sightings were ruled out as likely baleen whale sightings. Two sightings were within the known habitat in the northeastern GOMx, in waters of an appropriate depth suggesting they were likely Bryde's-like whales. Two sightings had useful photographs indicating a baleen whale with a distinctive falcate dorsal fin and were likely either a Bryde's whale or a stray sei whale. The four remaining sightings were in depths consistent with Bryde's whales, and several of these had descriptions of behavior consistent with them as well, e.g., two or more vertical blows before diving. These four sightings could not be ruled out based on the available information. While significant uncertainty remains with respect to the identity of whales sighted by PSO observers, four of the sightings were made along the continental shelf break west of the Mississippi River Delta (Figure 4).

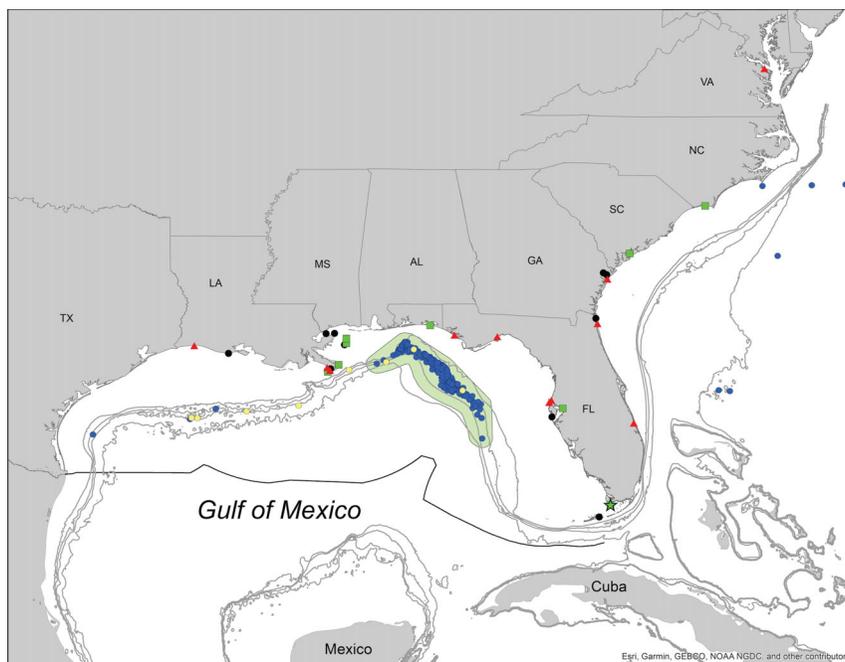


FIGURE 4 Distribution of all sightings and strandings of Bryde's-like whales in the Gulf of Mexico and Atlantic U.S. EEZ. All visual survey sightings (blue circles) recorded as “Bryde's,” “Bryde's/sei,” and “*Balaenoptera* sp.” whales during NMFS vessel and aerial surveys from 1992 to 2019, including all sightings listed as “Bryde's/sei whales” or “*Balaenoptera* sp.” in the western North Atlantic and sightings recorded by protected species observers (PSO) on seismic vessels (yellow circles) that could potentially have been a baleen whale. All strandings recorded as “Bryde's whales” (red triangle; presence of rostral ridges confirmed in stranding record or photos) or unconfirmed Bryde's-like whale (black circle; could not confirm presence of rostral ridges in stranding record), and genetically confirmed Gulf of Mexico Bryde's-like whale (green square) through May 2019, including the extralimital strandings in the western North Atlantic. Green polygon represents the core habitat for the whales in the northeastern Gulf of Mexico. The 100 m, 200 m, 400 m, and 1,000 m isobaths and the U. S. EEZ are shown.

3.3.2 | Atlantic Ocean

There are no confirmed at-sea sightings of any type of Bryde's whale along the U.S. eastern seaboard during NMFS marine mammal vessel and aerial surveys between 1992 and 2019, despite considerable survey effort in the U.S. EEZ from Florida through Maine (~854,721 km of on-effort track line surveyed). There were five ship-based and one aerial survey-based sightings recorded as “Bryde's/sei whales” from the early 1990s (Figure 4). None of these sightings were close enough to identify rostral ridges and five were in waters >1,000 m suggesting they were either the pelagic form of Bryde's whale (*B. e. brydei*) or were sei whales. The southernmost sighting of a Bryde's/sei whale in the Atlantic was in approximately 1,100 m water depth over the Blake Plateau east of central Florida, again much deeper than typical of the GOMx whales. Using 23 years of visual survey data from 1992 to 2014, Roberts et al. (2016) built habitat-based spatial density models for multiple cetacean species in U.S. waters of the western North Atlantic and GOMx. For the U.S. east coast, the authors utilized data collected from a variety of vessel- and aerial-based line transect surveys covering 895,000 km of effort from southern Florida to the Bay of Fundy. They predicted a mean monthly abundance of seven Bryde's whales (CV = 0.58) along the entire eastern seaboard based on four Bryde's/sei whale sightings recorded on these surveys (Roberts et al., 2016).

Acoustic studies have also not recorded whale call types associated with any type of Bryde's whale in the waters off Jacksonville, Florida, although fin, minke, *B. acutorostrata*, and sei whale vocalizations were detected (Frasier

et al., 2016). Further north off Cherry Point, North Carolina, and in Norfolk Canyon, acoustic monitoring has detected several baleen whale species, but to date no Bryde's whales have been recorded (Debich et al., 2014; Rafter et al., 2018). Overall, the evidence to date indicates Bryde's whales are extremely rare in U.S. waters of the western North Atlantic.

Of great interest is whether the Bryde's-like whales from the GOMx are distributed outside of the GOMx in the Caribbean. In other areas of the western Atlantic, Bryde's whales have been recorded off Brazil (de Moura & Siciliano, 2012; Gonçalves et al., 2016; Lodi et al., 2015; Maciel et al., 2018), Suriname (de Boer, 2015) and north to at least Venezuela (Romero et al., 2001; Smultea et al., 2013), and into the southern Caribbean including waters of Bonaire (Debrot et al., 1998), Aruba (Luksenburg et al., 2015), and Curacao (Debrot, 1998; Debrot et al., 1998). Luksenburg et al. (2015) genetically identified the Aruba strandings as *B. e. brydei* and found they were genetically closest to the whales sampled off Madeira in the eastern Atlantic. Whales stranded in Brazil have also been genetically confirmed as *B. e. brydei* (Pastene et al., 2015). Finally, there is a record of a live stranded Bryde's whale (subspecies unknown) from St. Vincent and the Grenadines in 2009.²

There are no comprehensive Caribbean-wide cetacean diversity studies from which to draw, and no Caribbean strandings north of Aruba have been genetically tested. However, based on existing sighting information it appears there is a hiatus of Bryde's whales in the central Caribbean, with *B. e. brydei* present in waters south of the hiatus and any Bryde's whale taxon generally rare north of it. A ship-board survey for cetaceans in 2000 covered waters from Puerto Rico to Venezuela (excluding Antigua and Barbuda, Dominica, and St. Vincent and the Grenadines) and recorded five Bryde's whale sightings, all in the southeastern Caribbean (Swartz & Burks, 2000), but which subspecies was seen is unknown. Similarly, Yoshida et al. (2010) surveyed from St. Kitts and Nevis south to Grenada and observed six Bryde's whales (subspecies unknown), all restricted to the southern survey area. One sighting was made in shallow waters northeast of Grenada while the remaining sightings were made in deep waters (2,000 m) of the Grenada and the Tobago basins. Additional surveys in the northern Caribbean have not recorded any subspecies of Bryde's whales (Roden & Mullin, 2000; Swartz et al., 2002).

Debrot et al. (2013) compiled cetacean records for the Dutch Windward Islands (Saba, St. Eustatius, St. Maarten, and the Saba Bank) and noted a surprising lack of records of any Bryde's whales. The authors suggested they may be absent from the northeastern Caribbean, a result in agreement with results from the shipboard surveys.

In the eastern Atlantic Ocean, Bryde's whales have been reported from the offshore islands of Cape Verde (Hazevoet & Wenzel, 2000), Madeira (Alves et al., 2010), and the Azores (Steiner et al., 2008). They also inhabit near-shore waters and offshore waters of the southwestern African coast (Best, 2001; Weir, 2010). To date, the whales in these regions have been genetically ascribed to Bryde's whales, *B. e. brydei*, (Luksenburg et al., 2015; Penry et al., 2018; Rosel & Wilcox, 2014), except for whales in the Azores and the Gulf of Guinea, which have not yet been genetically tested. Thus, to date, these studies have supported the conclusion by Rice (1998) that Eden's whale (*B. e. edeni*) is not present in the Atlantic.

3.3.3 | Stranding data

After compiling the available data from stranding reports from the GOMx and the U.S. Atlantic coast, we found 33 records that could potentially be Bryde's-like whales, 24 in the GOMx, and 9 in the Atlantic. We removed two of the GOMx records we identified as either duplicate records or misidentifications (or both) (Table S3), leaving 22 stranding records in the GOMx listed as "Bryde's whale," dating as far back as 1954; of these, 11 were found in Louisiana at or east of the Mississippi River Delta, nine were collected along the GOMx coast of Florida, including the Everglades, and two were collected in western Louisiana (Figure 4). Two stranded animals were recorded in the 1970s, seven in the 1980s, and four in 1990s, while three were recorded in the 2000s and four in the 2010s. The remaining two were recorded in 1954 and 1965. We characterized the 22 strandings further (Table 4) as (1) "verified GOMx Bryde's-like whale" when diagnostic DNA sequence data were retrieved from the specimen; (2) "Bryde's-like

TABLE 4 Compilation of unconfirmed Bryde's-like whale (identified in stranding record as a baleen whale or "Bryde's whale" but no description or photos to confirm presence of rostral ridges), Bryde's-like whale (identified in stranding record as a "Bryde's whale" and with written description or photos to confirm presence of rostral ridges), and verified Gulf of Mexico Bryde's-like whale (confirmed via genetic analysis) strandings in the northern Gulf of Mexico and U.S. eastern seaboard. Lengths are noted as being actual measured length (a) or estimated lengths (e) as noted in the stranding data records.

Catalog number	Additional identifiers	Date (mm/dd/yy)	Location	Latitude (°N)	Longitude (°W)	Length (cm)	Sex	Verification	Data and source for verification	Additional citations
Gulf of Mexico										
LSUMZ 17027	STR338	June 1954	Chandeleur Islands, St. Bernard Parish, LA	29.83	88.83	n/a	n/a	verified GOMx Bryde's-like whale	genetics; present study	Lowery, 1974; Mead, 1977; Schmidly, 1981; Jefferson, 1995
MME 2		8/18/82	2 km SE of Isle au Pitre, LA	30.13	89.18	1,500 (e)	n/a	unconfirmed Bryde's-like whale	no photos or notation of rostral ridges	Jefferson, 1995
SEAN 7128		12/25/82	Southwest Pass, LA	29.03	89.32	1,160 (e)	n/a	unconfirmed Bryde's-like whale	no photos or notation of rostral ridges	Jefferson, 1995
MME 1486	SE2250	11/8/85	Chandeleur Islands, Near Palos Island, LA	29.79	88.89	1,040 (a)	M	unconfirmed Bryde's-like whale	Top of head could not be accessed, cannot confirm ridges present. Ventral grooves reach to umbilicus. Likely Bryde's whale	Jefferson, 1995
MME 1939	SE2589, MME01956	10/28/86	Cameron Parish, LA	29.77	93.33	990 (e)	M	Bryde's-like whale	photos show ridges; Harris 1987	Harris & Richard, 1987; Jefferson, 1995
MME 5967	SE4790; 90-1-1	1/8/90	Freshwater Bayou Canal, 1/2 Mile West of Mouth, Intracoastal City, LA	29.53	92.32	1,067 (e)	n/a	unconfirmed Bryde's-like whale	no photos or notation of rostral ridges	Jefferson, 1995
MME 6574	SE5716, MM9101	1/7/91	1/4 M West of Bunces Pass, Saint Petersburg, FL	27.65	82.75	1,120	n/a	unconfirmed Bryde's-like whale	no photos or notation of rostral ridges	Jefferson, 1995
MME 7822	SE6168, MME7822, DRC-91-09	5/24/91	No Name Key, in Bogue Channel/ Big Pine Key, or Grassy Key, FL	24.72	81.35	1,140/ 1,158 (e)	n/a	unconfirmed Bryde's-like whale	no photos or notation of rostral ridges	Jefferson, 1995
MME 8837	SE8092, LA001-93	6/14/93	Le Petit Pass Island, LA	30.12	89.43	1,128 (a)	F	unconfirmed Bryde's-like whale	no photos or notation of rostral ridges	Jefferson, 1995
MME 11756	SE4038, SWF-BE-8876-B	11/25/88	Honeymoon Island, off Clearwater, FL	28.08	82.83	693	F	Bryde's-like whale	photos; Eds et al. 1993	Jefferson, 1995

(Continues)

TABLE 4 (Continued)

Catalog number	Additional identifiers	Date (mm/dd/yy)	Location	Latitude (° N)	Longitude (° W)	Length (cm)	Sex	Verification	Data and source for verification	Additional citations
STR 339		4/2/65	Panacea, FL	30.03	84.37	1,158	n/a	Bryde's-like whale	photos; Rice 1965	Lowery, 1974; Mead, 1977; Schmidt, 1981; Shane & Schmidt, 1976
STR 1923 = STR 2507		1/11/75	West Bay Region Near Venice/ near Tiger Pass, LA	29.12	89.40	841	M	Bryde's-like whale	visual observation of ridges; Shane and Schmidtly 1976	Mead, 1977; Schmidt, 1981;
USNM 504074	BAP001, CSLP7674	5/29/74	Tarpon Springs, Andote Key, FL	28.15	82.77	1,000	M	Bryde's-like whale	photos; Mead 1977	Gunter & Overstreet, 1974; Schmidt, 1981; Jefferson, 1995
UF33536	USNM 593536; MIMPL0906; SER09-0394	10/4/09	Tampa Bay, FL	27.91	82.43	1,265 (a)	F	verified GOMx Bryde's-like whale	genetics; Rosel and Wilcox 2014	
USNM 593537	FLGM110206-32; SER06-575	11/2/06	Walton County, FL	30.37	86.35	470 (e)	F	verified GOMx Bryde's-like whale	genetics; Rosel and Wilcox 2014	
0521Be	SER05-767	3/28/05	Southwest Pass, LA	28.99	89.38	914 (a)	F	verified GOMx Bryde's-like whale	genetics; Rosel and Wilcox 2014	
RKB-1403	SE4022	8/20/88	Panama City, FL	30.08	85.64	450 (p)	unk	Bryde's-like whale	baleen, throat groove location, size; R. K. Bonde unpublished	Jefferson, 1995
LSUMZ 033431	LSUMZ03343	2/28/82	near Southwest Pass, LA	29.07	89.29	n/a	n/a	baleen whale	no photos or notation of rostral ridges	Jefferson, 1995
MCT20120326	SER12-0585	3/18/12	North edge of Chandeleur Islands chain, LA	29.98	88.83	701 (p)	n/a	verified GOMx Bryde's-like whale	genetics; present study	
SMM20121101	SER12-0771	10/25/12	Lonesome Bayou, SE corner of Breton Sound, LA	29.20	89.06	780 (p)	M	verified GOMx Bryde's-like whale	genetics; present study	
44DISL091616	SER16-00537	9/15/16	25 miles offshore Louisiana, trawl	n/a	n/a	n/a	n/a	baleen whale	bone only	
USNM 594665	FMM5N1908, SER19-00187	1/29/19	Everglades National Park, FL	25.03	81.02	1,126 (a)	M	verified GOMx Bryde's-like whale	genetics; present study	holotype

(Continues)

TABLE 4 (Continued)

Catalog number	Additional identifiers	Date (mm/dd/yy)	Location	Latitude (° N)	Longitude (° W)	Length (cm)	Sex	Verification	Data and source for verification	Additional citations
Atlantic										
USNM 239307		3/18/1923	Walnut Point, VA	37.98	76.47	801-803	M	Bryde's-like whale	photos	Mead, 1977
USNM 572922	WAM 587	3/13/03	Carolina Beach, NC	34.07	77.88	1,105 (a)	M	verified GOMx Bryde's-like whale	genetics; Rosel and Wilcox 2014	
MME 8115	SC-92-1, SE6591	1/24/92	Ash Island, St. Helena Sound, SC	32.5	80.45	790 (a)	F	verified GOMx Bryde's-like whale	genetics; Rosel and Wilcox 2014	
MME 93	GA83010501	1/5/83	Osabaw Island, GA	31.74	81.11	660 (e)	n/a	Bryde's-like whale	Stranding record indicates rostral ridges present	
MME 11032	SE8345, GA83010501	9/18/93	Osabaw Island, GA	31.87	81.13	510 (a)	n/a	unconfirmed Bryde's-like whale	Highly decomposed. No photos or notation of rostral ridges	
SEAN 1209		11/6/76	Fort Pierce, FL	27.47	80.33	559	F	Bryde's-like whale	photos with stranding record	Schmidly, 1981
USNM 504768	SEAN3080, SE0028	3/14/78	Fort George Island, FL	30.42	81.41	869 (a)	M	Bryde's-like whale	photos; Leatherwood and Reeves 1983	Schmidly, 1981.
MME 3360		8/30/87	Amelia Island, FL	30.57	81.45	975	n/a	unconfirmed Bryde's-like unconfirmed Bryde's-like whale	No photos, animal swam away	
SEAN 3212	SE0064, HNN-884,	4/30/78	"Orange Canal between Ogeechee river and Rockfish creek"	31.92	81.23	950-953	M	unconfirmed Bryde's-like whale	No photos or notation of rostral ridges	Schmidly, 1981

whale” when stranding records included photos or written records indicating rostral ridges were present, but no genetic data were available; or (3) “unconfirmed Bryde's-like whale” when, although the stranding was recorded as a Bryde's whale, we could not find records (photographs, written notes) indicating rostral ridges were present and no tissues were available. Whales in category 2 are most likely GOMx Bryde's-like whales as we have found no genetic evidence for any other Bryde's-like subspecies in the GOMx, and there is little reason to doubt the records from category 3 as being GOMx Bryde's-like whales, but we chose to be conservative in our verification process. Following this categorization, we had tissue from seven and were able to confirm the mtDNA control region haplotype diagnostic of the Bryde's-like whales from the GOMx in all seven, including the 1954 skull collected by Lowery (1974). Six Gulf strandings had photos that clearly showed rostral ridges indicative of all members of the Bryde's whale complex, but no tissue was available for genetic analysis. The remaining nine could not be verified further than “baleen whale” following our conservative methods. Seven of those stranded in the northern GOMx in Louisiana, along the panhandle of Florida, or near Tampa, Florida where verified GOMx whale strandings are most common, suggesting it is likely these were also GOMx Bryde's-like whales. Interpretations for the other two, one stranding in Big Pine Key, Florida and the other in western Louisiana, are more difficult.

In the Atlantic, six of the nine records of “Bryde's whale” strandings included sufficient information to verify the animals were from the Bryde's whale complex, either because the records stated that photos were available to confirm rostral ridges or the skull or tissue was collected. Two of these six were confirmed genetically to match the Bryde's-like whales from the GOMx, having the diagnostic mtDNA control region haplotype. Three other records listed as Bryde's whale could not be confirmed either because decomposition of the carcass precluded observation of characteristic features of Bryde's whales or because the stranded animal was not documented well enough. Interestingly, all nine whales were relatively small; all but one was less than 1,000 cm in length (Table 4). Mead (1977) has suggested that the Bryde's whale strandings along the U.S. Atlantic were likely extralimital strays from the Gulf of Mexico.

In addition to the records for the southern Caribbean mentioned previously, there are five stranding records for Bryde's whales in the northern Caribbean but the subspecies of each is unknown. These include a stranded Bryde's whale in Puerto Rico reported in Mignucci-Giannoni et al. (1999) and a record in the Division of Mammals Collections at the Smithsonian National Museum of Natural History of a stranding in the Bahamas on March 4, 2000 (STR 12575) listed as “*B. edeni?*”. There is a second record of a Bryde's whale stranding in the Bahamas in 2008 (Currie et al., 2019), and both the USNM database and the Southeast U.S. stranding database reference a May 1991 stranding of a Bryde's whale in St. Croix, Lesser Antilles (MME7994, SE6423). Additional information to verify these records was not found. Whitt et al. (2011) reviewed records of marine mammals in Cuban waters and indicated one confirmed record of a Bryde's whale stranding from the southeastern coast of Cuba, but the subspecies is unknown. This animal was initially identified as a juvenile sei whale by Varona (1965). Mead (1977) reclassified it as a Bryde's whale as the bristles of the baleen were considered too coarse to be from a sei whale, although reports indicated no accessory ridges on the rostrum. Varona (1973), as reported in Whitt et al. (2011), suggested that sei whales were historically found off southeastern Cuba in the 1800s but it is possible these were misidentifications of Bryde's whales (Whitt et al., 2011).

4 | DISCUSSION

Rosel and Wilcox (2014) revealed, based on a genetic analysis of mtDNA control region sequences compiled from a worldwide distribution, that the Bryde's-like whales found in the northern GOMx were evolutionarily distinct from all other lineages and indicated that they may deserve taxonomic status on par with the other members of the Bryde's whale complex, *B. e. edeni* and *B. e. brydei*. Augmenting this study with additional samples from the GOMx for genetic analysis and with the first morphological analysis an intact specimen from the GOMx further supports

that these whales are taxonomically unique. The new morphological data provide a second, independent line of evidence as recommended for delimiting cetacean species (Reeves et al., 2004).

Several characteristics of the bones of the vertex of the skull distinguish the whales in the GOMx from all members of the Bryde's whale complex. They are clearly distinguished from Omura's whales by the extent of the premaxilla, which do reach the frontal bones in the whales from the GOMx but not in Omura's whales. Bryde's-like whales from the GOMx are easily distinguished from Eden's whales, *B. e. edeni*, by the fact that the frontals are only narrowly exposed between the ascending process of the maxilla and the supraoccipital. Finally, like *B. e. edeni* and *B. e. brydei*, the whales from the GOMx exhibit their own diagnostic shape of the nasal bones, and exhibit the unique feature of frontal bones wrapping around the smooth, curved posterior tips of the nasal bones and extending down in between the nasal bones, forcing a bigger gap between them than seen in the other subspecies. These features allow separation of Bryde's-like whales in the GOMx from Omura's whales and the two recognized subspecies of Bryde's whales.

Analysis of 18 new soft tissue samples and 1 bone sample, almost doubling the sample size used in the original analysis (Rosel & Wilcox, 2014), did not change the outcomes of the mtDNA genetic analysis or conclusion that these whales are genetically divergent from other whales in the genus *Balaenoptera*. Following the guidelines and standards for delimiting cetacean species and subspecies proposed by Taylor, Archer, et al. (2017), we find that the whales in the GOMx substantially exceed the recommended threshold for species for net nucleotide divergence (i.e., $d_A > 0.02$). When compared to the two recognized subspecies of Bryde's-like whales and to the sei whale, values of d_A for Bryde's-like whales in the GOMx ranged from 0.10 to 0.13 (10–13%) based on the first 375 bp of the mtDNA control region (Table 3). This level is equivalent to that seen between the two currently recognized subspecies of Bryde's whales ($d_A = 0.10$). Thus, the whales from the GOMx are as divergent as the currently recognized subspecies are from each other (and all three exceed the threshold for species). Taylor, Archer, et al. (2017) also recommended that, at the species level, two taxa must be diagnosably distinct, and specifically that there is a near 100% probability of identifying an individual as belonging to the taxon. Fixed nucleotide differences in the control region, such as exist between Bryde's-like whales from the GOMx and all other whales, serve to render them diagnosably distinct (100%), further meeting the quantitative criteria of being a separate species. Given the larger number of fixed differences in the control region (Table 3), additional mtDNA data, such as whole mitogenomes, is not likely to alter the diagnosability of these whales. In fact, Rosel and Wilcox (2014) identified multiple fixed differences in the cytochrome *b* and cytochrome oxidase I genes as well. For further perspective, Penry et al. (2018) compared mtDNA control region sequences from inshore and offshore ecotypes of Bryde's whale, *B. e. brydei*, off South Africa. Based on a 1.8%–2.1% divergence and 10 fixed differences, they concluded the two ecotypes off South Africa represent different subspecies. The values for both metrics are an order of magnitude lower than those observed between the Bryde's whales-like in the GOMx and the two recognized subspecies, further illustrating the significant evolutionary divergence exhibited by the whales in the GOMx.

Phylogenetic analysis of the control region sequences continues to identify Bryde's-like whales from the GOMx as a unique lineage separated from the two Bryde's whale subspecies and from the sei whale and Omura's whale with strong support (Figure 2). What the control region sequence data do not clearly answer is to which of the two subspecies these whales are most closely related. Posterior probabilities on the nodes joining the clades representing each taxon are very low, and in fact the phylogenetic tree based on the 375 bp alignment creates a trichotomy of the sei whale, *B. e. brydei*, and a joint *B. e. edeni* + GOMx whale clade, which itself has a posterior probability of only .61, well below the threshold (.90–.95) recognized for robust conclusions concerning phylogenetic relationships (Huelsenbeck & Rannala, 2004). This result is not uncommon for the control region, which performs well at identifying unique taxonomic groups and, for instance is useful for DNA barcoding of cetacean species (Viricel & Rosel, 2012), but has been shown to have limitations in identifying evolutionary relationships among recently diverged cetacean taxa (e.g., Perrin et al., 2013). Further analyses utilizing a larger data set that includes nuclear DNA sequences will provide a more robust investigation of the evolutionary relationships among these taxa.

In addition to genetic and morphological data, Bryde's-like whales in the GOMx also have a unique acoustic signature that distinguishes them from all other baleen whales. Rice et al. (2014) recorded acoustic calls using marine

autonomous recording units (MARUs) placed in the known whale habitat in the northeastern GOMx. Three types of sounds were recorded that were consistent with other baleen whale species, but none matched known sounds produced by other baleen whales, including the two Bryde's whale subspecies, suggesting these whales in the GOMx exhibit a unique and diagnostic acoustic repertoire; however, because the recorders were autonomous, it was not possible to directly link the recorded sounds to visual sightings of the whales (Rice et al., 2014). Širović et al. (2014) definitively identified a call-type directly associated with Bryde's-like whales in the GOMx through visual observation paired with towed acoustic-array recordings. More recently, long moans and downsweep pulse trains were validated to be from these whales in the GOMx using real-time visual and acoustic observations (M. Soldevilla, personal communication, April 2019).

A workshop on the taxonomy of cetaceans concluded that a single line of evidence (e.g., genetic data or morphological data) was sufficient to delimit cetacean subspecies while two independent lines of evidence were necessary for delimiting species (Reeves et al., 2004). Bryde's-like whales in the GOMx exhibit two strong lines of evidence that distinguish them from all other closely related species. Examination of morphological features of the skull, key to discriminating among taxa in the Bryde's whale complex and Omura's whale (Wada et al., 2003), revealed multiple diagnostic characters that distinguish the whales in the GOMx from both *B. e. edeni* and *B. e. brydei*, and from Omura's whale. Similarly, the degree of genetic divergence between the whales in the GOMx and *B. e. edeni* and *B. e. brydei* ($d_A > 0.10$) significantly exceeds the net divergence metric identified by Taylor, Archer, et al. (2017) for species delimitation based on mtDNA control region sequences ($d_A > 0.02$), and multiple diagnostic sites in the mitochondrial sequence further support divergence at the species level. The apparent highly restricted range and isolation of these whales in the northern GOMx reinforces a severely limited opportunity for gene flow with any other populations of Bryde's whales, and the morphological differences rule out recent or ongoing male-mediated gene flow. The data presented here from multiple lines of evidence (genetics, morphology, distribution) indicate that the Bryde's-like whales in the GOMx are a previously unnamed species.



FIGURE 5 Localities of published Bryde's-like whale observations in the greater Atlantic Ocean. Brown circles represent observations that were also genetically identified as *B. edeni brydei*. Blue circles represent observations that did not include genetic information. Green polygon represents core habitat identified in the northeastern Gulf of Mexico.

4.1 | Distribution

The Bryde's-like whales in the GOMx are the only year-round resident baleen whale species in the GOMx. Sightings and strandings of all other baleen whale species in the GOMx are rare and considered extralimital (Jefferson, 1995; Jefferson & Schiro, 1997). Compiling the sighting, acoustic, genetic, and stranding data, it is clear that these whales are restricted in their distribution to the GOMx, and that the northeastern GOMx, particularly the De Soto Canyon area and water depths of 150–410 m, are currently the primary habitat of these whales. The nearest confirmed populations of other members of the Bryde's whale complex are of *B. e. brydei* in the southern Caribbean south to Venezuela and Brazil, and in the eastern North Atlantic and the eastern south Atlantic off South Africa (Alves et al., 2010; Best, 2001; de Boer, 2015; de Moura & Siciliano, 2012; Debrot, 1998; Debrot et al., 1998; Gonçalves et al., 2016; Hazevoet & Wenzel, 2000; Hazevoet et al., 2010; Luksenburg et al., 2015; Maciel et al., 2018; Pastene et al., 2015; Penry et al., 2018) (Figure 5). To date there are no confirmed records of *B. e. edeni* from the Atlantic basin.

LaBrecque et al. (2015) identified biologically important areas (BIAs) for cetacean species in the GOMx, including waters 100–300 m deep in an area in the northeastern GOMx for the GOMx whale (see figure 3.1 in LaBrecque et al., 2015). We have revisited and updated this area using additional years of sighting data to better reflect the currently known core distribution in the northeastern GOMx (Figures 4 and 5). A convex hull polygon (IUCN, 2012) was drawn around all visual sightings recorded as “Bryde's whale,” “Bryde's/sei whale,” or “balaenopterid whale” (the latter are cases where the characteristic rostral ridges of a Bryde's whale were not noted), telemetry tag locations ($n = 52$) from a single Bryde's-like whale tagged in 2010 (Soldevilla et al., 2017) in the northeastern GOMx, and Acousonde tag locations ($n = 41$) for one whale tagged in 2015 (Soldevilla et al., 2017); a total of 212 data points collected between 1989 and 2018. The convex hull polygon was trimmed at 410 m, determined based on the current deepest known sighting of 408 m. By its very nature, many of the sightings fall on the boundary of the convex hull polygon and therefore the polygon underestimates the range of the species and was further buffered to account for uncertainty in the distribution. A 10 km buffer was drawn around this polygon to capture the uncertainty in sighting position given the strip width of the vessel surveys. An additional 20 km buffer was then added to this “position uncertainty” to account for the likely movement of observed whales. This results in a 30 km buffer around sighting locations. The area should be updated periodically with new sighting data as they become available.

As mentioned above, there was a confirmed sighting of a Bryde's-like whale in the western GOMx in 2017 and there were two baleen whale sightings (only identified as “Bryde's/sei whale”) during NMFS surveys in the western Gulf in the early 1990s. These sightings raise important questions. Is it possible that some whales move west from the current core habitat in the northeastern GOMx? Alternatively, do these sightings constitute remnants of a once more broadly distributed population, as suggested by whaling data (Reeves et al., 2011) and if so, why are they now rare in the western GOMx? Or do they come from another, as yet unidentified population in the southern GOMx? Has this area in the western GOMx become a marginal or suboptimal habitat for these whales? Further research in the western and southern GOMx will greatly aid our understanding of whether these whales utilize these habitats and if so, how often, and also how they are related to the whales that are found in the northeastern GOMx.

4.2 | Life history

Little is known about the life history of these whales in the GOMx. Stranding and biopsy data indicate both sexes are present in the Gulf; the sex ratio determined for 32 individual whales from the northern GOMx was 18 females and 14 males (not significantly different from a 50:50 ratio, Chi-square with one degree of freedom, $p = .4795$). In addition, stranding data indicate the whales are likely breeding in the GOMx, as we identified records of several smaller animals in the stranding records, including a 470 cm calf that stranded alive in November of 2006, and a

693 cm individual that stranded in November of 1988 and was brought into captivity for a short time (Edds et al., 1993). In August 2016, two whales were sighted together in the northeastern GOMx core area during a NMFS SEFSC large-vessel survey. One whale was approximately half the size of the larger whale and had physical characteristics suggestive of a calf. In addition, a dead, lactating female whale was found in Tampa Bay in October of 2009. This whale mortality likely resulted from a ship strike as the whale exhibited internal injuries consistent with blunt force trauma.

Basic information on total length, standard external measurements, external color pattern, etc. suffers from inadequate sample sizes. After reexamining records for strandings recorded as “Bryde's whales” in the GOMx and western North Atlantic, and removing those we determined to be mis-identified or duplicate records, some external measurements were available in common across eight whales (Table S4). Total length measurements for these whales ranged from 470 cm to 1,265 cm.

Worldwide, members of the Bryde's complex exhibit a variety of foraging strategies and prey preferences, often with observations of surface feeding. Overall, pelagic schooling fishes in the order Clupeiformes (sardines, herring, menhaden, anchovies) are the most commonly recorded prey, along with similar schooling species such as members of the family Carangidae (Best, 2001; Konishi et al., 2009; Murase et al., 2007; Siciliano et al., 2004; Tershy, 1992; Watanabe et al., 2012). Populations examined further offshore also target euphausiids (Best, 2001; Konishi et al., 2009), while the *B. e. brydei* population of the Hauraki Gulf in New Zealand appears to prey on copepods and krill along with ray-finned fishes and salps (Carroll et al., 2019). However, diet is poorly characterized for the whales in the GOMx. Surface feeding has never been observed. Recently, Soldevilla et al. (2017) placed an Acousonde suction-cup tag on a Bryde's-like whale in the northeastern GOMx. The tag remained attached for nearly 3 days (63.85 hr) in September 2015 and revealed a diel diving pattern. During the night, the whale remained near the surface, 88% of the time within 15 m of the surface. Daytime dive behavior was characterized by repeated deep dives to depths >200 m, likely at or near the seafloor. Some of these deep dives included lunges near the seafloor associated with foraging (Soldevilla et al., 2017). This type of bottom feeding is unusual for members of the complex. It is not known what they may have been feeding on at those depths. Lanternfish (Myctophidae) and hatchetfish (Sternoptychidae) are abundant members of pelagic waters of the GOMx (Ross et al., 2010; Stickney & Torres, 1989), and some species may serve as prey. Further work to identify primary prey species and foraging behaviors is needed and will be important for identifying potential threats and important habitat for these whales.

Finally, estimates of abundance for the whales in the northern GOMx are under 100 individuals. Broad-scale aerial and ship-based line transect surveys to estimate cetacean abundance have been conducted in the northern GOMx as far back as 1991. Eleven abundance estimates have been made between 1991 and 2009 and range between 0 and 44 (see Rosel et al., 2016 for summary of surveys). Surveys with the lowest estimates covered waters primarily of the western GOMx, supporting their rarity in this region. It should be noted, however, none of these surveys were focused on estimating abundance of a rare species and precision of all estimates is poor. The current best estimate of abundance is 33 (CV = 1.07; Waring et al., 2015). Future work dedicated to estimating abundance within the known habitat in the northeastern GOMx is needed.

4.3 | Conservation status

The small population size and associated deleterious genetic effects (e.g., inbreeding depression, loss of potentially adaptive genetic diversity and accumulation of deleterious mutations), and the restricted distribution alone, place these whales at high risk of extinction and they are of grave conservation concern. They recently have been listed as Endangered under the U.S. Endangered Species Act of 1973 and are listed as a Critically Endangered subpopulation on the IUCN Red List (Corkeron et al., 2017). Additional significant threats include vessel collisions, anthropogenic noise during seismic surveys, habitat destruction, modification or curtailment of habitat range during energy

FIGURE 6 Deformation to tail stock, possibly resulting from a ship strike in a Bryde's-like whale from the northern Gulf of Mexico. Photo credit: NMFS SEFSC under MMPA permit.



exploration and development, oil spills and oil spill response, and marine debris (Rosel et al., 2016). Fishery interactions may also pose a threat, but more research is necessary to determine the level of impact from this threat (Rosel et al., 2016; Soldevilla et al., 2017). The recent analyses of dive behaviors by Soldevilla et al. (2017) indicate these whales may feed near the seafloor in a region where some bottom longline fishing occurs, raising the risk of fishery interactions. The surface behavior identified by the same study suggests these whales may spend a considerable amount of time at night within the first 15 m of the water column. This behavior significantly raises the risk of ship strikes. Two whales have shown evidence for ship strike. An adult, lactating female stranded in Tampa Bay, Florida with injuries, including separated vertebral, lung damage, and subdermal contusions, consistent with impact caused by a large object. In 2019, a free-swimming whale was observed in the northeastern GOMx with a severely deformed spine posterior to the dorsal fin consistent with a vessel strike (Figure 6). These two cases illustrate the anthropogenic threat that vessels may pose to this population. Finally, the 2019 whale that stranded in the Everglades (FMMSN1908, USNM 594665) was found to have a sharp piece of intragastric plastic approximately 6.6 l x 6.2 w x 0.2 d cm in dimension. The plastic caused hemorrhaging and acute gastric necrosis in the second stomach chamber. The whale was thin and because the necropsy identified no other infections or pathologies that could be attributed to the animal's death, it was concluded that the ingestion of the plastic led to the stranding and subsequent mortality of this whale.

Continued efforts to fully characterize dive behavior, feeding strategies, and prey preference will improve management strategies for this Endangered whale. In addition, ongoing research to determine whether they regularly use habitat in the western and/or southern GOMx will aid our understanding of their distribution. If they are shown to use these waters with regularity, further work to determine the relationship of such whales to those utilizing the northeastern GOMx is critical to developing a full picture of the status and range of these whales. Finally, a better understanding of whether they once were a component of the ecosystem in the north-central and western GOMx, as suggested by Reeves et al. (2011) based on Yankee whaling records, prior to the extensive alteration of habitat through energy exploration and development is needed. If they previously utilized habitat in the western GOMx, understanding why they may have abandoned the habitat will significantly aid conservation and recovery plans for these whales.

4.4 | Conclusion

The data presented here provide multiple lines of evidence (genetics, morphology, distribution) indicating that the Bryde's-like whales in the GOMx are a previously unnamed species. The morphological and genetic lines of evidence that distinguish these whales in the GOMx as a new species also provide equivalent support for reelevating the two subspecies of *B. edeni* to species level, *B. edeni* Anderson, 1879 and *B. brydei* Olsen, 1913. Here, the only species that would then utilize the English name Bryde's whale would be *B. brydei*, the larger, more pelagic baleenopterid distributed world-wide in tropical and subtropical oceans. Eden's whale would refer to *B. edeni*, the smaller animals found, to date, in coastal and shelf waters of the tropical and subtropical Indian and western Pacific Oceans. The terms

“Bryde's-like whale” and “Bryde's whale complex” would not be necessary anymore. Future investigation of other coastal populations, such as the population off the coast of south Africa (Best, 1977, 2001; Penry et al., 2018) may continue to identify new subspecies.

We recognize the lingering unfinished, but ongoing, taxonomic work in this group, i.e., genetically verifying the holotype of *B. edeni* and the need to identify and designate a neotype specimen and its associated genetic signature for *B. brydei*. Some may not yet support species rank for these lineages, but might rather support continued recognition of subspecies status until these underlying taxonomic details are worked out. However, a convincing volume of evidence, both morphological and genetic, has grown substantially in recent years (Kershaw et al., 2013; Penry et al., 2018; Rosel & Wilcox, 2014; Sasaki et al., 2006; Wada et al., 2003; Yamada et al., 2006, 2008) and multiple independent lines of evidence are consistent with species level differences for all members of the “Bryde's whale complex” and now for the new evolutionarily distinct species found in the GOMx.

4.5 | Systematics

Order Cetartiodactyla Montgelard, Catzefils and Douzery, 1997

Cetacea Brisson, 1762

Family Balaenopteridae Gray, 1864

Genus *Balaenoptera* Lacépède, 1804

Balaenoptera ricei sp. nov.

Rice's whale

Figures 3, 7, 8; Table 1; Figures S8–S10

4.5.1 | Holotype and Type Locality

USNM 594665, an adult male, 1,126 cm, stranded on January 29, 2019, near Flamingo, Florida Bay, Gulf of Mexico, at the outer edge of Everglades National Park, Florida (25.0344°N, 81.0185°W). The skull (Figures 7 and S10) and complete skeleton and baleen are deposited in the U.S. National Museum of Natural History. The full mtDNA control region sequence for the holotype has been placed in GenBank with accession number MN017985.

4.5.2 | Additional Material

Lowery (1974) reported a skull found on the Chandeleur Islands, St. Bernard Parish, Louisiana, in June 1954. This specimen is housed in the Louisiana State University Museum of Natural Science (LSUMZ 17027) and was originally identified as a fin whale. We sequenced the mitochondrial DNA control region of this specimen and identified it as a Rice's whale. Unfortunately, the skull is missing a number of important bones, including the premaxillae, nasals, lacrimals, jugals, and pterygoid hamuli. Photographs of the skull are in Lowery (1974) and Figures S3 and S4.

A complete skull and skeleton of a 1,105 cm immature male whale that stranded in New Hanover County, North Carolina (34.07°N, 77.88°W) on March 13, 2003 was deposited in the U.S. National Museum of Natural History under specimen number USNM 572922. The whale was genetically confirmed to be a Rice's whale (Rosel & Wilcox, 2014). Best (2007) published photographs of the skull of this specimen and assigned it as *B. edeni*. Photographs of the skull are also in Figure S5.

On October 4, 2009, a 1,265 cm adult female whale stranded in Tampa Bay, Florida (27.91°N, 82.43°W) and the carcass was buried in Fort De Soto Park, Pinellas County, Florida. The whale was genetically confirmed as a

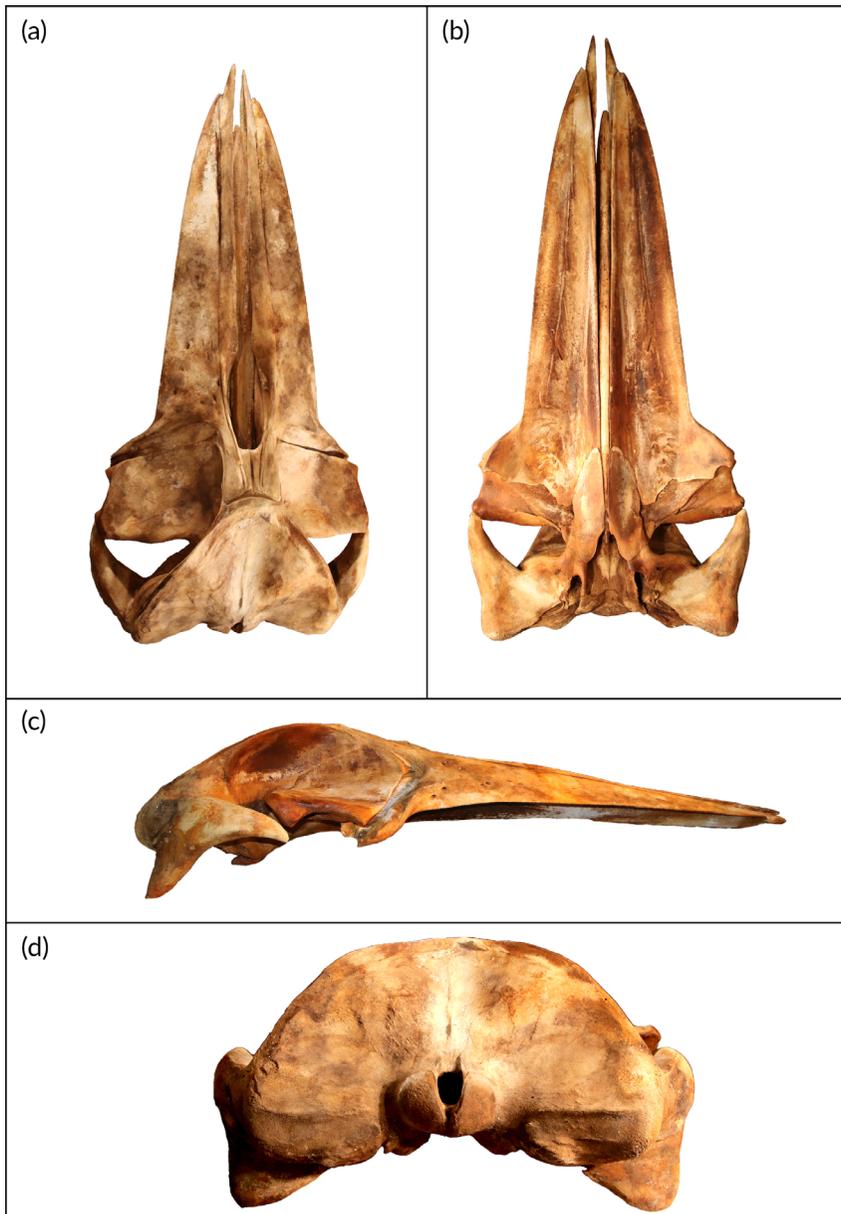


FIGURE 7 Images of (a) dorsal, (b) ventral, (c) right lateral, and (d) caudal views of the skull of Rice's whale (holotype specimen USNM 594665).

Rice's whale (Rosel & Wilcox, 2014). In March 2018, the remains were excavated in the hopes of finding an intact skull to serve as a type specimen. Unfortunately, the skull had been crushed during burial and most of the specimen lay in water for the 9 years it was buried. The remains of the skull and a nearly complete vertebral column were retrieved and deposited in the Florida Museum of Natural History in Gainesville, Florida with accession number UF33536.

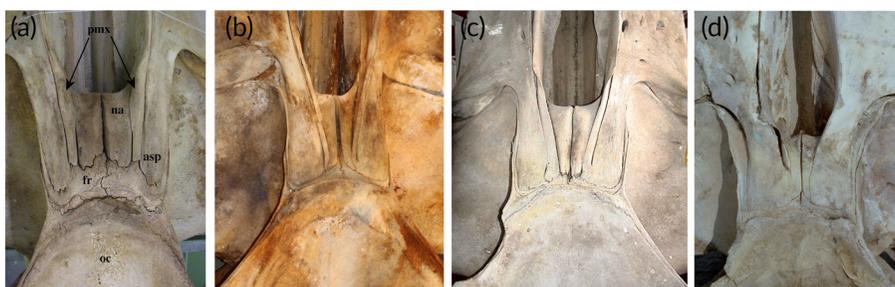


FIGURE 8 Vertex of the skulls of (a) Eden's whale, *B. e. edeni* (RMNH4003), (b) Rice's whale, *B. ricei* (USNM 594665, holotype), (c) Bryde's whale, *B. e. brydei* (CKU HL19990729), and (d) Omura's whale, *B. omurai* (NSMT M32505). pmx = premaxilla, na = nasal, asp = ascending process of the maxilla, fr = frontal, oc = occipital.

4.5.3 | Diagnosis

Balaenoptera ricei differs from *B. e. edeni* and *B. e. brydei* in the following morphological features: the nasals taper and curve laterally at the posterior end and have a smooth margin, meeting the medial-posterior margin of the ascending process of the maxilla; there is a broad gap between the nasal bones that does not narrow posteriorly created in part by the frontal bones which protrude anteriorly between the posterior end of the nasals (Figure 8). Rice's whale can also be differentiated from all other species of rorqual baleen whales based on molecular genetic characters, as shown in the phylogenetic analyses of the mtDNA control region (Table 3, Figure 2). Within the 305 base pair alignment of the 5' end of the mtDNA control region, ten diagnostic sites differentiate *B. ricei* from both *B. e. brydei* and *B. e. edeni* (Table 2).

4.5.4 | Description

The Rice's whale is a medium-sized rorqual whale. They appear to be larger than Omura's whales and smaller than Bryde's whales, *B. e. brydei*, but, based on limited samples, about the same size as Eden's whales. To date, the largest verified Rice's whale was 1,265 cm in length (a lactating female) and the largest male was 1,126 cm. Rice's whales have a falcate dorsal fin (Figure S6). In the holotype specimen, the dorsal fin was located approximately 2/3 of the way back from the snout. The flippers are uniformly dark. Although sample sizes are small, the ventral grooves/pleats reach to or just past the umbilicus; in the holotype specimen 1 pleat extended 36 cm past the umbilicus and two additional pleats extended past the umbilicus but were not measured (Table S4). The number of pleats counted on the holotype specimen at the flipper insertion was 27 to the central midline making a total of 54 pleats. These whales exhibit no external asymmetrical pigmentation on the lower jaws, thereby differentiating them from the asymmetrical jaw coloration seen in fin whales and Omura's whales. Body color is uniformly dark charcoal gray above, including both the upper and lower jaws, and light to pinkish countershading ventrally. Some whales exhibit diffuse white washes on the body around the base of the dorsal fin and/or along the sides but to date no consistency in the pattern across individuals has been seen (Figure S7). The fringe of the baleen plates is uniformly cream colored throughout the entire rack, the anterior baleen plates are cream colored on both sides, with a distinct posterior transition to black plates (Figure 3). Plate count for the holotype specimen was 264 on the left side. A total of 224 plates were counted on the right side but approximately 60 cm of the baleen rack of the right side was not accessible making this is an incomplete count. Mead (1977) and Kato and Perrin (2018) indicated that the baleen bristles of members of the Bryde's whale complex are coarser than those of sei whales, and we can confirm, based on a sample size of three, that the baleen bristles of Rice's whales from the GOMx are coarser than that of a sei whale that stranded in the

GOMx in 1994. However, no comprehensive analysis of bristle diameter across all the Bryde's whale taxa has yet been performed.

The vertebral formula of the holotype is cervical (7) + thoracic (13) + lumbar (13) + caudal (20) = 53. There were 13 ribs on either side and the head of each first rib is bifurcated.

Several other unique features were noted in the skeleton of the holotype. Junge (1950), Lönnberg (1931), and Omura (1959) describe the stylohyal bones of Bryde's whales as generally longer than they are wide with some degree of curvature. The stylohyal bones of the holotype of *B. ricei* had little curvature to them and are very broad (Figure S9). In addition, the pelvic bones of the holotype specimen are nearly straight, with only a very small projection on one side (Figure S9).

4.5.5 | Etymology

The specific name, *ricei*, is in honor of renowned American cetologist Dale W. Rice (1930–2017). We choose this species name to commemorate Dale W. Rice who had a distinguished 60-year career in marine mammal science and wrote the seminal volume “Marine Mammals of the World” (Rice, 1998), which provided the first comprehensive worldwide review of the systematics and distribution of all marine mammal species. He was the first researcher to recognize that Bryde's whales are present in the GOMx (Rice, 1965). We propose Rice's whale as the common English name. Naming it after a person is consistent with the other members of the complex: Eden's whale (*B. e. edeni*) having been named after Ashley Eden, a British Commissioner (Anderson, 1878 [1879]), Bryde's whale (*B. e. brydei*) named after Johan Bryde, a Norwegian businessman and whaler (Olsen, 1913), and Omura's whale (*B. omurai*) was named after the Japanese cetologist Hideo Omura (Wada et al., 2003). We note that the common name ‘Gulf of Mexico whale’ has been used for this species.

4.5.6 | Nomenclatural Statement

A Life Science Identifier (LSID) was obtained for this publication: [urn:lsid:zoobank.org:pub:ACA4D8E5-1373-4D26-931F-0A657EEDE4CC](https://zoobank.org/pub/ACA4D8E5-1373-4D26-931F-0A657EEDE4CC).

4.5.7 | Comparison

Externally, Rice's whale is separated from all other balaenopterid whales except those in the Bryde's whale complex by the presence of three longitudinal ridges on the rostrum; one in the center and two lateral ridges (Figure 1). Omura's whale lacks these prominent lateral ridges, instead having faint ridges visible only in certain viewing conditions (Cerchio et al., 2015).

As described in Wada et al. (2003), the vertex of the skull, including the shapes and extent of the ascending process of the maxilla (APM), the nasals, frontals, premaxillae serve as much of the defining morphological characteristics that separate members of the Bryde's whale complex (Figure 8). In this region, *B. ricei* is clearly differentiated from *B. e. edeni* by the shape and extent of the ascending process of the maxilla which broaden only slightly at the posterior end, more similar in shape to *B. e. brydei* than *B. omurai* or *B. e. edeni*, with *B. e. edeni* being distinctive in its slender ascending process of the maxilla with rounded posterior end (Figures 8 and S10). *B. ricei* also differs from *B. e. edeni* in the shape of the nasals (triangular versus rectangular), and the extent of the frontals, which are exposed as a thin strip or belt between the ascending processes of the maxilla, the posterior end of the nasals and the supraoccipital, rather than the broad exposure of the frontals seen in *B. e. edeni*. *B. ricei* is most easily differentiated from *B. omurai* by the posterior end of the premaxillae which reach the frontals in *B. ricei* but not in *B. omurai*

(Figure 8). In addition, the alisphenoid is in contact with the squamosal (Figure S8) while it is separated from the squamosal bone in *B. omurai* (Wada et al., 2003). Finally, *B. ricei* can be distinguished from *B. e. brydei* by the shape of the posterior end of the nasals which curve laterally and have smooth margins, while in *B. e. brydei* the posterior end of the nasals remains relatively straight and the posterior margin is crenulated. In addition, the frontal bones wrap around and extend anteriorly into the space between the posterior end of the nasals, creating a significant space or gap between the nasal bones along their entire length.

Finally, *B. ricei* is unambiguously discriminated from all other balaenopterid whales by DNA sequence of the mitochondrial genome. Ten diagnostic sites in the 5' end of the mitochondrial control region (between nucleotide positions 15536–15818 of the *B. e. brydei* mtDNA genome GenBank accession number AB201259) separate *B. ricei* from all members of the Bryde's whale complex (Table 2). Similarly, mitochondrial cytochrome *b* and cytochrome oxidase I genes exhibit multiple fixed differences between *B. ricei* and *B. e. edeni*, *B. e. brydei*, and *B. omurai* (Rosel & Wilcox, 2014).

4.5.8 | Distribution

Based on vessel and aerial survey sightings, the primary core habitat of Rice's whale is currently in the northeastern GOMx, centered over the De Soto Canyon in waters between 150 and 410 m depth (Figure 4). Recently there was a genetically confirmed sighting in the western GOMx off the central Texas coast in 225 m water depth (National Marine Fisheries Service, 2018), and preliminary analysis of acoustic recordings from the western GOMx along the shelf break south of the Flower Garden Banks National Marine Sanctuary suggest the presence of Bryde's-like whales (M. Soldevilla, personal communication, April 2019) in the same area as two balaenopterid sightings made by NMFS in the early 1990s (Figure 4). While contemporary sightings are primarily confined to the northeastern GOMx, it is possible the species historically had a broader distribution in the GOMx. Reeves et al. (2011) reviewed whaling logbooks from the GOMx and identified records of “finback” whales from the north central Gulf south of the Mississippi River delta and in the southern Gulf on the Campeche Banks. As fin whales are not part of the GOMx ecosystem, these were likely Rice's whales misidentified as fin whales (Reeves et al., 2011), suggesting the whale's distribution was broader than we see today.

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AUTHOR CONTRIBUTIONS

Patricia Rosel: Conceptualization; data curation; formal analysis; funding acquisition; investigation; methodology; project administration; supervision; validation; visualization; writing-original draft; writing-review and editing. **Lynsey Wilcox:** Data curation; formal analysis; investigation; methodology; project administration; writing-review and editing. **Tadasu Yamada:** Formal analysis; investigation; methodology; writing-review and editing. **Keith Mullin:** Conceptualization; investigation; visualization; writing-review and editing.

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ENDNOTES

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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IEEFA: Analysis finds U.S. can increase LNG shipments to Europe without building new facilities

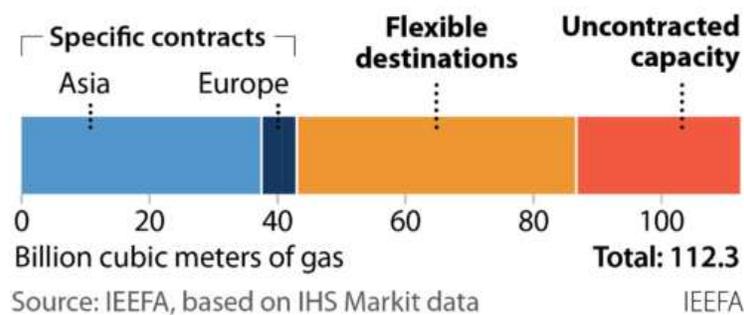
Balancing act required for LNG to meet Europe gas needs without jeopardizing long-term climate goals

April 6, 2022 (IEEFA)—The U.S. can increase shipments of liquefied natural gas (LNG) to Europe that will replace declining gas imports from Russia—without building new plants, according to [an analysis by the Institute for Energy Economics and Financial Analysis](#).

The White House and European leaders announced plans in late March to boost U.S gas shipments to Europe by at least 15 billion cubic meters this year. Although the fossil fuel industry is citing the European energy crisis as reason to build more LNG facilities, the IEEFA analysis found the U.S. LNG industry is on track to far exceed its target, without the construction of any new LNG plants.

U.S. LNG Third-Party Sales Contracts, 2022

Flexible contracts and spare capacity give the U.S. LNG industry ample room to ship more LNG to Europe.



“We’ve seen a huge boom in shipments of U.S. LNG to Europe in the first quarter of this year,” said Clark Williams-Derry, an IEEFA energy finance analyst and author of the report. “A combination of increased output from U.S. plants and flexible contracts has allowed much more U.S. LNG to flow to Europe.”

Europe’s appetite for LNG has been boosted by its desire to reduce the continent’s dependence on Russian gas in the wake of its invasion of Ukraine. European leaders hope to replace the Russian supply that provides more than 40 percent of its natural gas imports through demand reduction and, in the short term, through increased LNG purchases.

The increased LNG demand from Europe, however, has helped drive global LNG prices to their highest level in history, with Europe bidding against the rest of the world for a limited supply of LNG. High prices, limited supplies, and cargo cancellations have cooled demand for the fuel in Asia, and may be encouraging emerging economies to rethink their LNG import plans.

Rising LNG exports have also boosted natural gas prices in the U.S. As the country exports more natural gas, it is effectively importing higher prices. Building new plants to supply Europe could make the problem worse, and could also make it difficult for the continent to meet its long-term climate goals.

“Our findings suggest that building new LNG infrastructure in the U.S. could be a long-term financial mistake,” said Williams-Derry. “The U.S. is on track to meet European LNG supply goals using the plants it has, and new plants could face long-term challenges from fickle Asian demand and Europe’s climate commitments.”

Full Report: [The U.S. Can Increase LNG Exports to Europe](#)

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About IEEFA: The [Institute for Energy Economics and Financial Analysis](#) (IEEFA) examines issues related to energy markets, trends and policies. IEEFA’s mission is to accelerate the transition to a diverse, sustainable and profitable energy economy.

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April 2021

BRYDE'S WHALE (*Balaenoptera edeni*): Northern Gulf of Mexico Stock

STOCK DEFINITION AND GEOGRAPHIC RANGE

Bryde's whales are distributed worldwide in tropical and sub-tropical waters, but the taxonomy and number of species and/or subspecies of Bryde's whales in the world is currently a topic of debate (Kato and Perrin 2008, Rosel and Wilcox 2014). In the western Atlantic Ocean, Bryde's whales are reported from the Gulf of Mexico and the southern West Indies to Cabo Frio, Brazil (Leatherwood and Reeves 1983). Sighting records and acoustic detections of Bryde's whales in the northern Gulf of Mexico (i.e., U.S. Gulf of Mexico) occur almost exclusively in the northeastern Gulf in the De Soto Canyon area, along the continental shelf break between 100 m and 400 m depth, with a single sighting at 408 m (Figure 1; Hansen *et al.* 1996, Mullin and Hoggard 2000, Mullin and Fulling 2004, Maze-

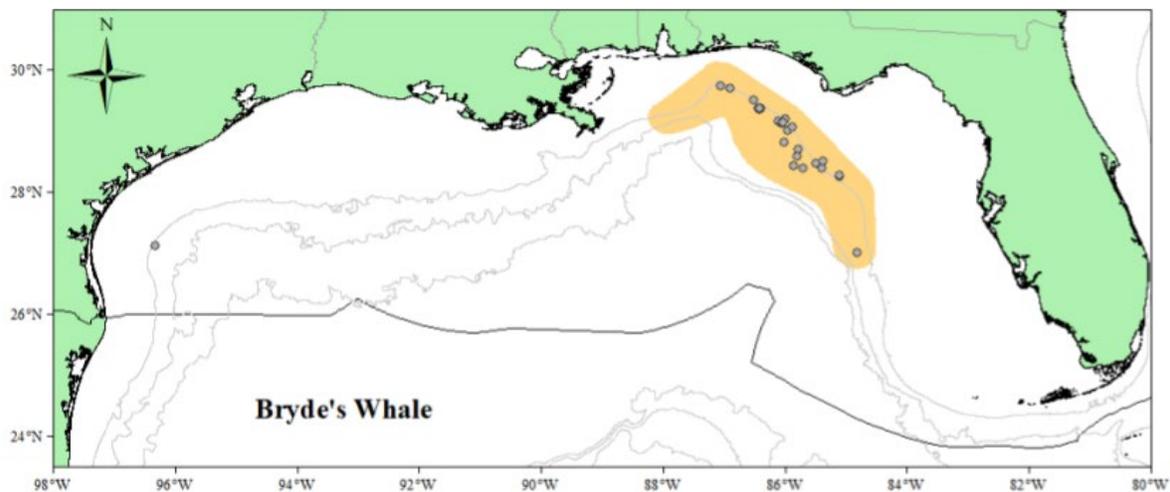


Figure 1. Distribution of all Bryde's whale sightings from SEFSC vessel surveys during spring 1996–2001, summer 2003, spring 2004, summer 2009, summer 2017, and summer/fall 2018. Isobaths are the 200-m, 1,000-m, and 2,000-m depth contours. The darker line indicates the U.S. EEZ. The shaded area indicates the core habitat.

Foley and Mullin 2006, Rice *et al.* 2014; Rosel and Wilcox 2014; Širović *et al.* 2014; Rosel *et al.* 2016; Soldevilla *et al.* 2017). Bryde's whales have been sighted in all seasons within the De Soto Canyon area (Mullin and Hoggard 2000, Maze-Foley and Mullin 2006, Mullin 2007, DWH MMIQT 2015). Genetic analysis suggests that Bryde's whales from the northern Gulf of Mexico represent a unique evolutionary lineage distinct from other recognized Bryde's whale subspecies, including those found in the southern Caribbean and southwestern Atlantic off Brazil (Rosel and Wilcox 2014). The geographic distribution of this Bryde's whale form has not yet been fully identified. Two strandings from the southeastern U.S. Atlantic coast share the same genetic characteristics with those from the northern Gulf of Mexico (Rosel and Wilcox 2014), but it is unclear whether these are extralimital strays (Mead 1977) or whether they indicate the population extends from the northeastern Gulf of Mexico to the Atlantic coast of the southern U.S. (Rosel and Wilcox 2014). There have been no confirmed sightings of Bryde's whales along the U.S. east coast during NMFS cetacean surveys (Rosel *et al.* 2016).

Historical whaling records from the 1800s suggest Bryde's whales may have been more common in the U.S. waters of the north central Gulf of Mexico and in the southern Gulf of Mexico in the Bay of Campeche (Reeves *et al.* 2011). How regularly they currently use U.S. waters of the western Gulf of Mexico is unknown. There has been only one confirmed sighting of a Gulf of Mexico Bryde's whale in this region, a whale observed during a 2017 NMFS vessel survey off Texas, despite substantial NMFS survey effort in the north central and western Gulf dating back to

the early 1990s (e.g., Hansen *et al.* 1996; Mullin and Hoggard 2000; Mullin and Fulling 2004; Maze-Foley and Mullin 2006). A compilation of available records of cetacean sightings, strandings, and captures in Mexican waters of the southern Gulf of Mexico identified no Bryde's whales (Ortega-Ortiz 2002). There are insufficient data to determine whether it is plausible the stock contains multiple demographically independent populations that should be separate stocks.

POPULATION SIZE

The best abundance estimate available for Bryde's whales in the northern Gulf of Mexico is 51 (CV=0.50; Table 1). This estimate is from summer 2017 and summer/fall 2018 oceanic surveys covering waters from the 200-m isobath to the seaward extent of the U.S. EEZ (Garrison *et al.* 2020).

Earlier Abundance Estimates

Five point estimates of Bryde's whale abundance have been made based on data from surveys during: 2003 (June–August), 2004 (April–June), 2009 (July–August), 2017 (July–August), and 2018 (August–October). Each of these surveys had a similar design and was conducted using the same vessel or a vessel with a similar observation platform. Surveys in 2003, 2004, and 2009 employed a single survey team while the 2017 and 2018 surveys employed two survey teams. In addition, the 2017 and 2018 surveys were conducted in "passing" mode rather than "closing" mode. Passing mode eliminates the problems of fragmented tracklines associated with using closing mode in areas with high densities of animals. When using the closing mode with the two-team method, both teams must be allowed the opportunity to see a mammal group and allow it to pass behind the ship before turning to close on it, making it difficult to reacquire the group and resulting in long periods spent chasing the group, with the increased potential for off-effort sightings. For passive acoustics, in closing mode the vessel often turns before the acoustic team is able to achieve a good localization. This is especially important for deep-diving species where visual surveys are less optimal for abundance estimates. However, passing mode can result in increased numbers of unidentified sightings and may have affected group size estimation for distant groups of dolphins and small whales. Comparisons of the survey results over the years 2003 through 2009 required adjustments for these differences, including apportioning unidentified species among identified taxa to address the first issue, applying the model for detection probability on the trackline from the summer 2017 survey to the abundance estimates from the 2003, 2004, and 2009 surveys, and examining relationships between sighting distance and estimated group size (Garrison *et al.* 2020). This resulted in revised abundance estimates of: 2003, N=0 (CV=NA); 2004, N=64 (CV=0.88); and 2009, N=100 (CV=1.03).

Recent Surveys and Abundance Estimates

An abundance estimate for Bryde's whales was generated from vessel surveys conducted in the northern Gulf of Mexico from the continental shelf edge (~200-m isobath) to the seaward extent of the U.S. EEZ (Garrison *et al.* 2020). One survey was conducted from 2 July to 25 August 2017 and consisted of 7,302 km of on-effort trackline, and the second survey was conducted from 11 August to 6 October 2018 and consisted of 6,473 km of on-effort trackline. The surveys were conducted in passing mode (e.g., Schwarz *et al.* 2010) while all prior surveys in the Gulf of Mexico have been conducted in closing mode. Both surveys used a double-platform data-collection procedure to allow estimation of the detection probability on the trackline using the independent observer approach assuming point independence (Laake and Borchers 2004). Due to the restricted habitat range of Gulf of Mexico Bryde's whales, survey effort was re-stratified to include only effort within their core habitat area (Figure 1;

<https://www.fisheries.noaa.gov/resource/map/gulf-mexico-brydes-whale-core-distribution-area-map-gis-data>)

including 941 km of effort in 2017 and 848 km of effort in 2018. In addition, there was an insufficient number of Bryde's whale sightings during these surveys to develop an appropriate detection probability function. Therefore, a detection function was derived based on 91 sightings of Bryde's whale groups observed during SEFSC large vessel surveys between 2003 and 2019. The abundance estimates include unidentified large whales and baleen whales observed within the Bryde's whale habitat. However, the estimate does not include the sighting of a confirmed Bryde's whale in the western Gulf of Mexico in 2017. It is not possible to extrapolate estimated density beyond the core area since little is known about habitat use and distribution outside of this area. Estimates of abundance were derived using MCDS distance sampling methods that account for the effects of covariates (e.g., sea state, glare) on detection probability within the surveyed strip (Thomas *et al.* 2010) implemented in package *mrds* (version 2.21; Laake *et al.* 2020) in the R statistical programming language. The 2017 and 2018 estimates were N=84 (CV=0.92) and N=40 (CV=0.55), respectively. The inverse variance weighted mean abundance for Bryde's whales in oceanic waters during 2017 and 2018 was 51 (CV=0.50; Table 1; Garrison *et al.* 2020). This estimate was not corrected for the probability of detection on the trackline because there was only one resighting and few sightings overall of Bryde's whales during the two-team surveys.

Table 1. Most recent abundance estimate (*Nest*) and coefficient of variation (*CV*) of Bryde's whales in northern Gulf of Mexico oceanic waters (200 m to the offshore extent of the EEZ) based on the inverse variance weighted mean from summer 2017 and summer/fall 2018 vessel surveys.

Years	Area	Nest	CV
2017, 2018	Gulf of Mexico	51	0.50

Minimum Population Estimate

The minimum population estimate (N_{min}) is the lower limit of the two-tailed 60% confidence interval of the log-normally distributed best abundance estimate. This is equivalent to the 20th percentile of the log-normal distributed abundance estimate as specified by Wade and Angliss (1997). The best estimate of abundance for Bryde's whales is 51 ($CV=0.50$). The minimum population estimate for the northern Gulf of Mexico Bryde's whale is 34 (Table 2).

Current Population Trend

Using revised abundance estimates for surveys conducted in 2003 (June–August), 2004 (April–June), and 2009 (July–August; see above), and the 2017 (July–August) and 2018 (August–October) estimates, pairwise comparisons of the non-zero log-transformed means were conducted between years, and significant differences were assessed at $\alpha=0.10$. P-values were adjusted for multiple comparisons. There were no significant differences between survey years (Garrison *et al.* 2020).

However, the statistical power to detect a trend in abundance for this stock is poor due to the relatively imprecise abundance estimates and long intervals between surveys. For example, the power to detect a precipitous decline in abundance (i.e., 50% decrease in 15 years) with estimates of low precision (e.g., $CV>0.30$) remains below 80% ($\alpha=0.30$) unless surveys are conducted on an annual basis (Taylor *et al.* 2007). In addition, because these surveys are restricted to U.S. waters, it is not possible to distinguish between changes in population size and Gulf-wide shifts in spatial distribution.

All verified Bryde's whale sightings, with one exception, have occurred in a very restricted area of the northeastern Gulf (Figure 1) during surveys that uniformly sampled the entire oceanic northern Gulf. Because the population size is small, in order to effectively monitor trends in Bryde's whale abundance in the future, other methods need to be used.

CURRENT AND MAXIMUM NET PRODUCTIVITY RATES

Current and maximum net productivity rates are unknown for this stock. For purposes of this assessment, the maximum net productivity rate was assumed to be 0.04. This value is based on theoretical modeling showing that cetacean populations likely do not grow at rates much greater than 4% given the constraints of their reproductive life history (Barlow *et al.* 1995). Between 1988 and 2018, there have been two documented strandings of calves (total length <700 cm) in the northern Gulf of Mexico (SEUS Historical Stranding Database unpublished data; NOAA National Marine Mammal Health and Stranding Response Database unpublished data).

POTENTIAL BIOLOGICAL REMOVAL

Potential Biological Removal (PBR) is the product of the minimum population size, one-half the maximum net productivity rate and a recovery factor (MMPA Sec. 3.16 U.S.C. 1362; Wade and Angliss 1997; Wade 1998). The minimum population size is 34. The maximum productivity rate is 0.04, the default value for cetaceans. The recovery factor is 0.1 because the stock is listed as endangered. PBR for the northern Gulf of Mexico Bryde's whale is 0.1 (Table 2).

Table 2. Best and minimum abundance estimates for northern Gulf of Mexico Bryde's whales with Maximum Productivity Rate (*Rmax*), Recovery Factor (*Fr*) and PBR.

Nest	CV	N_{min}	Fr	Rmax	PBR
51	0.50	34	0.1	0.04	0.1

ANNUAL HUMAN-CAUSED MORTALITY AND SERIOUS INJURY

The total annual estimated fishery-related mortality and serious injury for the Gulf of Mexico Bryde's whale stock during 2014–2018 is unknown. There was no documented fishery-caused mortality or serious injury for this stock during 2014–2018 (Table 3). Mean annual mortality and serious injury during 2014–2018 due to other human-caused actions (the *Deepwater Horizon* oil spill) was predicted to be 0.5. The minimum total mean annual human-caused mortality and serious injury for this stock during 2014–2015 was, therefore, 0.5. This is considered a minimum mortality estimate as some fisheries with which the stock could interact have limited observer coverage. In addition, the likelihood is low that a whale killed at sea due to a fishery interaction or vessel-strike will be recovered (Williams *et al.* 2011).

Table 3. Total annual estimated fishery-related mortality and serious injury for northern Gulf of Mexico Bryde's whales.

Years	Source	Annual Avg.	CV
2014–2018	U.S. fisheries using observer data	Unknown	-

Fisheries Information

There are three commercial fisheries that overlap geographically and potentially could interact with this stock in the Gulf of Mexico. These include the Category I Atlantic Ocean, Caribbean, Gulf of Mexico large pelagics longline fishery, and two Category III fisheries, the Southeastern U.S. Atlantic, Gulf of Mexico shark bottom longline/hook-and-line fishery and the Southeastern U.S. Atlantic, Gulf of Mexico, and Caribbean snapper-grouper and other reef fish bottom longline/hook-and-line fishery. See Appendix III for detailed fishery information. All three of these fisheries have observer programs, however observer coverage is limited for the two Category III fisheries.

Pelagic swordfish, tunas, and billfish are the targets of the large pelagics longline fishery operating in the northern Gulf of Mexico. During 2014–2018 there were no observed mortalities or serious injuries to Bryde's whales by this fishery (Garrison and Stokes 2016, 2017, 2019, 2020a, 2020b). Percent observer coverage (percentage of sets observed) for this longline fishery for each year during 2014–2018 was 18, 19, 23, 13 and 20, respectively. For the two category III bottom longline/hook-and-line fisheries, the target species are large and small coastal sharks and reef fishes such as snapper, grouper, and tilefish. There has been no reported fishery-related mortality or serious injury of a Bryde's whale by either of these fisheries (e.g., Scott-Denton *et al.* 2011; Gulak *et al.* 2013, 2014; Enzenauer *et al.* 2015, 2016; Mathers *et al.* 2017, 2018, 2020). Within the Gulf of Mexico, observer coverage for the snapper-grouper and other reef fish bottom longline fishery is ~1% or less annually, and for the shark bottom longline fishery coverage is 1–2% annually. Usually bottom longline gear is thought to pose less of a risk for cetaceans to become entangled than pelagic longline gear. However, if cetaceans forage along the seafloor, as is suspected for the Bryde's whale (Soldevilla *et al.* 2017), then there is an opportunity for these whales to become entangled in the mainline as well as in the vertical buoy lines (Rosel *et al.* 2016).

Two other commercial fisheries that overlap to a small degree with the primary Bryde's whale habitat in the northeastern Gulf of Mexico are the Category III Gulf of Mexico butterflyfish trawl fishery and Category II Southeastern U.S. Atlantic, Gulf of Mexico shrimp trawl fishery (Rosel *et al.* 2016). No interactions with Bryde's whales have been documented for either of these fisheries. There is no observer coverage for the butterflyfish trawl fishery. The shrimp trawl fishery has ~2% observer coverage annually.

Other Mortality

There were no reported strandings of Bryde's whales in the Gulf of Mexico during 2014–2018 (NOAA National Marine Mammal Health and Stranding Response Database unpublished data, accessed 21 May 2019). Stranding data probably underestimate the extent of human and fishery-related mortality and serious injury because not all of the whales that die or are seriously injured in human interactions wash ashore, or, if they do, they are not all recovered (Peltier *et al.* 2012, Wells *et al.* 2015). In particular, oceanic stocks in the Gulf of Mexico are less likely to strand than nearshore coastal stocks or shelf stocks (Williams *et al.* 2011). Additionally, not all carcasses will show evidence of human interaction, entanglement or other fishery-related interaction due to decomposition, scavenger damage, etc. (Byrd *et al.* 2014). Finally, the level of technical expertise among stranding network personnel varies widely as does the ability to recognize signs of human interaction.

An Unusual Mortality Event (UME) was declared for cetaceans in the northern Gulf of Mexico beginning 1 March 2010 and ending 31 July 2014 (Litz *et al.* 2014;

http://www.nmfs.noaa.gov/pr/health/mmume/cetacean_gulfofmexico.htm, accessed 1 June 2016). It included cetaceans that stranded prior to the *Deepwater Horizon* (DWH) oil spill (see “Habitat Issues” below), during the spill, and after. Exposure to the DWH oil spill was determined to be the primary underlying cause of the elevated stranding numbers in the northern Gulf of Mexico after the spill (e.g., Schwacke *et al.* 2014; Venn-Watson *et al.* 2015; Colegrove *et al.* 2016; DWH NRDAT 2016; see Habitat Issues section). Two Bryde's whale strandings in 2012 were considered to be part of this UME.

A population model was developed to estimate the injury and time to recovery for stocks affected by the DWH oil spill, taking into account long-term effects resulting from mortality, reproductive failure, reduced survival rates, and the proportion of the stock exposed to DWH oil (DWH MMIQT 2015). Based on the population model, it was projected that 2.3 Bryde's whales died during 2014–2018 (see Appendix VI) due to elevated mortality associated with oil exposure and that the stock experienced a 22% maximum reduction in population size due to the oil spill (DWH MMIQT 2015). The DWH Marine Mammal Injury Quantification Team cautioned that the capability of Bryde's whales to recover from the DWH oil spill is unknown because the population models do not account for stochastic processes and genetic effects (DWH MMIQT 2015), to which small populations are highly susceptible (Shaffer 1981; Rosel and Reeves 2000). The population model used to predict Bryde's whale mortality due to the DWH event has a number of sources of uncertainty. Model parameters (e.g., survival rates, reproductive rates, and life-history parameters) were derived from literature sources for Bryde's whales occupying waters outside of the Gulf of Mexico. In addition, proxy values for the effects of DWH oil exposure on both survival rates and reproductive success were applied based upon estimated values for common bottlenose dolphins in Barataria Bay. Finally, there was no estimation of uncertainty in model parameters or outputs.

HABITAT ISSUES

The *DWH* MC252 drilling platform, located approximately 80 km southeast of the Mississippi River Delta in waters about 1,500 m deep, exploded on 20 April 2010. The rig sank, and over 87 days, ~3.2 million barrels of oil were discharged from the wellhead until it was capped on 15 July 2010 (DWH NRDAT 2016). Shortly after the oil spill, the NRDA process was initiated under the Oil Pollution Act of 1990. A variety of NRDA research studies were conducted to determine potential impacts of the spill on marine mammals. These studies estimated that 48% of Bryde's whales in the Gulf were exposed to oil, that 22% (95%CI: 10–31) of females suffered from reproductive failure, and 18% (95%CI: 7–28) of the population suffered adverse health effects (DWH MMIQT 2015). A population model estimated the stock experienced a maximum 22% reduction in population size (see Other Mortality section above).

Vessel strikes also pose a threat to this stock (Soldevilla *et al.* 2017). In 2009, a Bryde's whale was found floating in the Port of Tampa, Tampa Bay, Florida. The whale had evidence of pre-mortem and post-mortem blunt trauma, and was determined to have been struck by a vessel, draped across the bow, and carried into port.

Anthropogenic sound in the world's oceans has been shown to affect marine mammals, with vessel traffic, seismic surveys, and active naval sonars being the main anthropogenic contributors to low- and mid-frequency noise in oceanic waters (e.g., Nowacek *et al.* 2015; Gomez *et al.* 2016; NMFS 2018). The long-term and population consequences of these impacts are less well-documented and likely vary by species and other factors. Impacts on marine mammal prey from sound are also possible (Carroll *et al.* 2017), but the duration and severity of any such prey effects on marine mammals are unknown.

STATUS OF STOCK

The Bryde's whale is listed as endangered under the Endangered Species Act, and therefore the northern Gulf of Mexico stock is considered strategic under the MMPA. The stock is very small and exhibits very low genetic diversity, which places the stock at great risk of demographic stochasticity. The stock's restricted range also places it at risk of environmental stochasticity. In addition, the mean modeled annual human-caused mortality and serious injury due to the DWH oil spill exceeds PBR for this stock. The status of Bryde's whales in the northern Gulf of Mexico, relative to OSP, is unknown. There was no statistically significant trend in population size for this stock.

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Climate Change 2022

Impacts, Adaptation and Vulnerability

Summary for Policymakers



WGII

Working Group II contribution to the
Sixth Assessment Report of the
Intergovernmental Panel on Climate Change



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Summary for Policymakers

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SPM.A: Introduction

This Summary for Policymakers (SPM) presents key findings of the Working Group II (WGII) contribution to the Sixth Assessment Report (AR6) of the IPCC¹. The report builds on the WGII contribution to the Fifth Assessment Report (AR5) of the IPCC, three Special Reports², and the Working Group I (WGI) contribution to the AR6 cycle.

This report recognizes the interdependence of climate, ecosystems and biodiversity³, and human societies (Figure SPM.1) and integrates knowledge more strongly across the natural, ecological, social and economic sciences than earlier IPCC assessments. The assessment of climate change impacts and risks as well as adaptation is set against concurrently unfolding non-climatic global trends e.g., biodiversity loss, overall unsustainable consumption of natural resources, land and ecosystem degradation, rapid urbanisation, human demographic shifts, social and economic inequalities and a pandemic.

The scientific evidence for each key finding is found in the 18 chapters of the underlying report and in the 7 cross-chapter papers as well as the integrated synthesis presented in the Technical Summary (hereafter TS) and referred to in curly brackets {}. Based on scientific understanding, key findings can be formulated as statements of fact or associated with an assessed level of confidence using the IPCC calibrated language⁴. The WGII Global to Regional Atlas (Annex I) facilitates exploration of key synthesis findings across the WGII regions.

¹ Decision IPCC/XLVI-3, The assessment covers scientific literature accepted for publication by 1 September 2021.

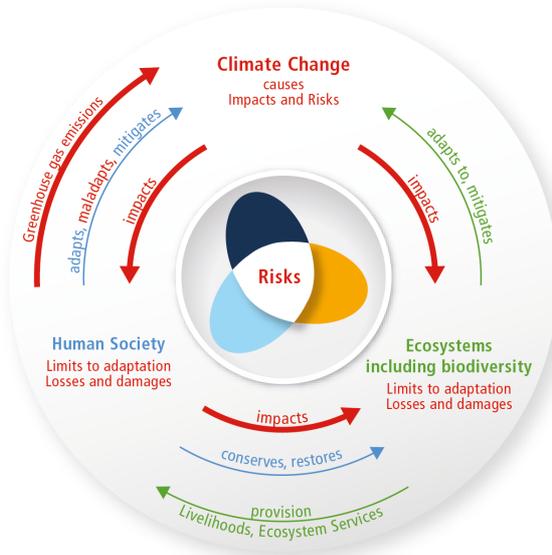
² The three Special Reports are: ‘Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty (SR1.5)’; ‘Climate Change and Land. An IPCC Special Report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems (SRCCL)’; ‘IPCC Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC)’

³ Biodiversity: Biodiversity or biological diversity means the variability among living organisms from all sources including, among other things, terrestrial, marine and other aquatic ecosystems, and the ecological complexes of which they are part; this includes diversity within species, between species, and of ecosystems.

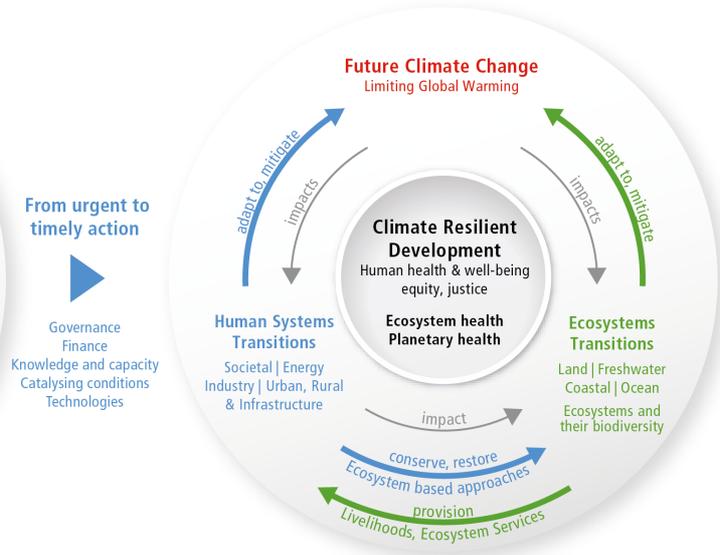
⁴ Each finding is grounded in an evaluation of underlying evidence and agreement. A level of confidence is expressed using five qualifiers: very low, low, medium, high and very high, and typeset in italics, e.g., *medium confidence*. The following terms have been used to indicate the assessed likelihood of an outcome or a result: virtually certain 99-100% probability, very likely 90-100%, likely 66-100%, as likely as not 33-66%, unlikely 0-33%, very unlikely 0-10%, exceptionally unlikely 0-1%. Assessed likelihood is typeset in italics, e.g., *very likely*. This is consistent with AR5 and the other AR6 Reports.

From climate risk to climate resilient development: climate, ecosystems (including biodiversity) and human society as coupled systems

(a) Main interactions and trends



(b) Options to reduce climate risks and establish resilience



The risk propeller shows that risk emerges from the overlap of:



Figure SPM.1: This report has a strong focus on the interactions among the coupled systems climate, ecosystems (including their biodiversity) and human society. These interactions are the basis of emerging risks from climate change, ecosystem degradation and biodiversity loss and, at the same time, offer opportunities for the future. (a) Human society causes climate change. Climate change, through hazards, exposure and vulnerability generates impacts and risks that can surpass limits to adaptation and result in losses and damages. Human society can adapt to, maladapt and mitigate climate change, ecosystems can adapt and mitigate within limits. Ecosystems and their biodiversity provision livelihoods and ecosystem services. Human society impacts ecosystems and can restore and conserve them. (b) Meeting the objectives of climate resilient development thereby supporting human, ecosystem and planetary health, as well as human well-being, requires society and ecosystems to move over (transition) to a more resilient state. The recognition of climate risks can strengthen adaptation and mitigation actions and transitions that reduce risks. Taking action is enabled by governance, finance, knowledge and capacity building, technology and catalysing conditions. Transformation entails system transitions strengthening the resilience of ecosystems and society (Section D). In a) arrow colours represent principle human society interactions (blue), ecosystem (including biodiversity) interactions (green) and the impacts of climate change and human activities, including losses and damages, under continued climate change (red). In b) arrow colours represent human system interactions (blue), ecosystem (including biodiversity) interactions (green) and reduced impacts from climate change and human activities (grey). {1.2, Figure 1.2, Figure TS.1}

The concept of risk is central to all three AR6 Working Groups. A risk framing and the concepts of adaptation, vulnerability, exposure, resilience, equity and justice, and transformation provide alternative, overlapping, complementary, and widely used entry points to the literature assessed in this WGII report.

Across all three AR6 working groups, **risk**⁵ provides a framework for understanding the increasingly severe, interconnected and often irreversible impacts of climate change on ecosystems, biodiversity, and human systems; differing impacts across regions, sectors and communities; and how to best reduce adverse

⁵ Risk is defined as the potential for adverse consequences for human or ecological systems, recognising the diversity of values and objectives associated with such systems

consequences for current and future generations. In the context of climate change, risk can arise from the dynamic interactions among climate-related **hazards**⁶ (see Working Group I), the **exposure**⁷ and **vulnerability**⁸ of affected human and ecological systems. The risk that can be introduced by human responses to climate change is a new aspect considered in the risk concept. This report identifies 127 key risks⁹. {1.3, 16.5}

The vulnerability of exposed human and natural systems is a component of risk, but also, independently, an important focus in the literature. Approaches to analysing and assessing vulnerability have evolved since previous IPCC assessments. Vulnerability is widely understood to differ within communities and across societies, regions and countries, also changing through time.

Adaptation¹⁰ plays a key role in reducing exposure and vulnerability to climate change. Adaptation in ecological systems includes autonomous adjustments through ecological and evolutionary processes. In human systems, adaptation can be anticipatory or reactive, as well as incremental and/ or transformational. The latter changes the fundamental attributes of a social-ecological system in anticipation of climate change and its impacts. Adaptation is subject to hard and soft limits¹¹.

Resilience¹² in the literature has a wide range of meanings. Adaptation is often organized around resilience as bouncing back and returning to a previous state after a disturbance. More broadly the term describes not just the ability to maintain essential function, identity and structure, but also the capacity for transformation.

This report recognises the value of diverse forms of **knowledge** such as scientific, as well as Indigenous knowledge and local knowledge in understanding and evaluating climate adaptation processes and actions to reduce risks from human-induced climate change. AR6 highlights adaptation solutions which are effective, **feasible**¹³, and conform to principles of **justice**¹⁴. The term climate justice, while used in different ways in different contexts by different communities, generally includes three principles: *distributive justice* which refers to the allocation of burdens and benefits among individuals, nations and generations; *procedural justice* which refers to who decides and participates in decision-making; and *recognition* which entails basic respect and robust engagement with and fair consideration of diverse cultures and perspectives.

⁶ Hazard is defined as the potential occurrence of a natural or human-induced physical event or trend that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems and environmental resources. Physical climate conditions that may be associated with hazards are assessed in Working Group I as climatic impact-drivers.

⁷ Exposure is defined as the presence of people; livelihoods; species or ecosystems; environmental functions, services and resources; infrastructure; or economic, social or cultural assets in places and settings that could be adversely affected.

⁸ Vulnerability in this report is defined as the propensity or predisposition to be adversely affected and encompasses a variety of concepts and elements, including sensitivity or susceptibility to harm and lack of capacity to cope and adapt.

⁹ Key risks have potentially severe adverse consequences for humans and social-ecological systems resulting from the interaction of climate related hazards with vulnerabilities of societies and systems exposed.

¹⁰ Adaptation is defined, in human systems, as the process of adjustment to actual or expected climate and its effects in order to moderate harm or take advantage of beneficial opportunities. In natural systems, adaptation is the process of adjustment to actual climate and its effects; human intervention may facilitate this.

¹¹ Adaptation Limits: The point at which an actor's objectives (or system needs) cannot be secured from intolerable risks through adaptive actions.

- Hard adaptation limit - No adaptive actions are possible to avoid intolerable risks.

- Soft adaptation limit - Options may exist but are currently not available to avoid intolerable risks through adaptive action.

¹² Resilience in this report is defined as the capacity of social, economic and ecosystems to cope with a hazardous event or trend or disturbance, responding or reorganising in ways that maintain their essential function, identity and structure as well as biodiversity in case of ecosystems while also maintaining the capacity for adaptation, learning and transformation. Resilience is a positive attribute when it maintains such a capacity for adaptation, learning, and/or transformation.

¹³ Feasibility refers to the potential for an adaptation option to be implemented.

¹⁴ Justice is concerned with setting out the moral or legal principles of fairness and equity in the way people are treated, often based on the ethics and values of society. *Social justice* comprises just or fair relations within society that seek to address the distribution of wealth, access to resources, opportunity and support according to principles of justice and fairness. *Climate justice* comprises justice that links development and human rights to achieve a rights-based approach to addressing climate change.

Effectiveness refers to the extent to which an action reduces vulnerability and climate-related risk, increases resilience, and avoids maladaptation¹⁵.

This report has a particular focus on transformation¹⁶ and system transitions in energy; land, ocean, coastal and freshwater ecosystems; urban, rural and infrastructure; and industry and society. These transitions make possible the adaptation required for high levels of human health and wellbeing, economic and social resilience, ecosystem health¹⁷, and planetary health¹⁸ (Figure SPM.1). These system transitions are also important for achieving the low global warming levels (WGIII) that would avoid many limits to adaptation¹¹. The report also assesses economic and non-economic losses and damages¹⁹. This report labels the process of implementing mitigation and adaptation together in support of sustainable development for all as climate resilient development²⁰.

[START BOX SPM.1 HERE]

Box SPM.1: AR6 Common Climate Dimensions, Global Warming Levels and Reference Periods

Assessments of climate risks consider possible future climate change, societal development and responses. This report assesses literature including that based on climate model simulations that are part of the fifth and sixth Coupled Model Intercomparison Project phase (CMIP5, CMIP6) of the World Climate Research Programme. Future projections are driven by emissions and/or concentrations from illustrative Representative Concentration Pathways (RCPs)²¹ and Shared Socio-economic Pathways (SSPs)²² scenarios, respectively²³. Climate impacts literature is based primarily on climate projections assessed in AR5 or earlier, or assumed global warming levels, though some recent impacts literature uses newer projections based on the CMIP6 exercise. Given differences in the impacts literature regarding socioeconomic details and assumptions, WGII chapters contextualize impacts with respect to exposure, vulnerability and adaptation as appropriate for their literature, this includes assessments regarding sustainable development and climate resilient development. There are many emissions and socioeconomic pathways that are consistent with a given global warming outcome. These represent a broad range of possibilities as available in the literature assessed that affect future climate change exposure and vulnerability. Where available, WGII also assesses literature that is based on an integrative SSP-RCP framework where climate projections obtained under the RCP scenarios are analysed against the backdrop of various illustrative SSPs²². The WGII assessment combines multiple lines of evidence including impacts modelling driven by climate projections, observations, and process understanding. {1.2, 16.5, 18.2, CCB CLIMATE, WGI SPM.C, WGI Box SPM.1, WGI 1.6, WGI Ch.12, AR5 WGI}

¹⁵ Maladaptation refers to actions that may lead to increased risk of adverse climate-related outcomes, including via increased greenhouse gas emissions, increased or shifted vulnerability to climate change, more inequitable outcomes, or diminished welfare, now or in the future. Most often, maladaptation is an unintended consequence.

¹⁶ Transformation refers to a change in the fundamental attributes of natural and human systems.

¹⁷ Ecosystem health: a metaphor used to describe the condition of an ecosystem, by analogy with human health. Note that there is no universally accepted benchmark for a healthy ecosystem. Rather, the apparent health status of an ecosystem is judged on the ecosystem's resilience to change, with details depending upon which metrics (such as species richness and abundance) are employed in judging it and which societal aspirations are driving the assessment.

¹⁸ Planetary health: a concept based on the understanding that human health and human civilisation depend on ecosystem health and the wise stewardship of ecosystems.

¹⁹ In this report, the term 'losses and damages' refers to adverse observed impacts and/or projected risks and can be economic and/or non-economic.

²⁰ In the WGII report, climate resilient development refers to the process of implementing greenhouse gas mitigation and adaptation measures to support sustainable development for all.

²¹ RCP-based scenarios are referred to as RCPy, where 'y' refers to the level of radiative forcing (in watts per square meter, or $W m^{-2}$) resulting from the scenario in the year 2100.

²² SSP-based scenarios are referred to as SSPx-y, where 'SSPx' refers to the Shared Socio-economic Pathway describing the socio-economic trends underlying the scenarios, and 'y' refers to the level of radiative forcing (in watts per square meter, or $W m^{-2}$) resulting from the scenario in the year 2100.

²³ IPCC is neutral with regard to the assumptions underlying the SSPs, which do not cover all possible scenarios. Alternative scenarios may be considered or developed.

A common set of reference years and time periods are adopted for assessing climate change and its impacts and risks: the reference period 1850–1900 approximates pre-industrial global surface temperature, and three future reference periods cover the near-term (2021–2040), mid-term (2041–2060) and long-term (2081–2100). {CCB CLIMATE}

Common levels of global warming relative to 1850–1900 are used to contextualize and facilitate analysis, synthesis and communication of assessed past, present and future climate change impacts and risks considering multiple lines of evidence. Robust geographical patterns of many variables can be identified at a given level of global warming, common to all scenarios considered and independent of timing when the global warming level is reached. {16.5, CCB CLIMATE, WGI 4.2, WGI CCB11.1, WGI Box SPM.1}

WGI assessed increase in global surface temperature is 1.09 [0.95 to 1.20]²⁴ °C in 2011–2020 above 1850–1900. The estimated increase in global surface temperature since AR5 is principally due to further warming since 2003–2012 (+0.19 [0.16 to 0.22] °C).²⁵ Considering all five illustrative scenarios assessed by WGI, there is at least a greater than 50% likelihood that global warming will reach or exceed 1.5°C in the near-term, even for the very low greenhouse gas emissions scenario²⁶. {WGI CCB 2.3, WGI SPM A1.2, WGI SPM B1.3, WGI Table SPM.1}

[END BOX SPM.1 HERE]

SPM.B: Observed and Projected Impacts and Risks

Since AR5, the knowledge base on observed and projected impacts and risks generated by climate hazards, exposure and vulnerability has increased with impacts attributed to climate change and key risks identified across the report. Impacts and risks are expressed in terms of their damages, harms, economic, and non-economic losses. Risks from observed vulnerabilities and responses to climate change are highlighted. Risks are projected for the near-term (2021–2040), the mid (2041–2060) and long term (2081–2100), at different global warming levels and for pathways that overshoot 1.5°C global warming level for multiple decades²⁷. Complex risks result from multiple climate hazards occurring concurrently, and from multiple risks interacting, compounding overall risk and resulting in risks transmitting through interconnected systems and across regions.

Observed Impacts from Climate Change

SPM.B.1 Human-induced climate change, including more frequent and intense extreme events, has caused widespread adverse impacts and related losses and damages to nature and people, beyond natural climate variability. Some development and adaptation efforts have reduced vulnerability. Across sectors and regions the most vulnerable people and systems are observed to be disproportionately affected. The rise in weather

²⁴ In the WGI report, square brackets [x to y] are used to provide the assessed *very likely* range, or 90% interval.

²⁵ Since AR5, methodological advances and new datasets have provided a more complete spatial representation of changes in surface temperature, including in the Arctic. These and other improvements have also increased the estimate of global surface temperature change by approximately 0.1°C, but this increase does not represent additional physical warming since AR5.

²⁶ Global warming of 1.5°C relative to 1850–1900 would be exceeded during the 21st century under the intermediate, high and very high greenhouse gas emissions scenarios considered in this report (SSP2-4.5, SSP3-7.0 and SSP5-8.5, respectively). Under the five illustrative scenarios, in the near term (2021–2040), the 1.5°C global warming level is *very likely* to be exceeded under the very high greenhouse gas emissions scenario (SSP5-8.5), *likely* to be exceeded under the intermediate and high greenhouse gas emissions scenarios (SSP2-4.5 and SSP3-7.0), *more likely than not* to be exceeded under the low greenhouse gas emissions scenario (SSP1-2.6) and *more likely than not* to be reached under the very low greenhouse gas emissions scenario (SSP1-1.9). Furthermore, for the very low greenhouse gas emissions scenario (SSP1-1.9), it is *more likely than not* that global surface temperature would decline back to below 1.5°C toward the end of the 21st century, with a temporary overshoot of no more than 0.1°C above 1.5°C global warming.

²⁷ Overshoot: In this report, pathways that first exceed a specified global warming level (usually 1.5°C, by more than 0.1°C), and then return to or below that level again before the end of a specified period of time (e.g., before 2100). Sometimes the magnitude and likelihood of the overshoot is also characterized. The overshoot duration can vary from at least one decade up to several decades.

and climate extremes has led to some irreversible impacts as natural and human systems are pushed beyond their ability to adapt. (*high confidence*) (Figure SPM.2) {1.3, 2.3, 2.4, 2.6, 3.3, 3.4, 3.5, 4.2, 4.3, 5.2, 5.12, 6.2, 7.2, 8.2, 9.6, 9.8, 9.10, 9.11, 10.4, 11.3, 12.3, 12.4, 13.10, 14.4, 14.5, 15.3, 16.2, CCP1.2, CCP3.2, CCP4.1, CCP5.2, CCP6.2, CCP7.2, CCP7.3, CCB EXTREMES, CCB ILLNESS, CCB SLR, CCB NATURAL, CCB DISASTER, CCB MIGRATE, Figure TS.5, TS B1}

SPM.B.1.1 Widespread, pervasive impacts to ecosystems, people, settlements, and infrastructure have resulted from observed increases in the frequency and intensity of climate and weather extremes, including hot extremes on land and in the ocean, heavy precipitation events, drought and fire weather (*high confidence*). Increasingly since AR5, these observed impacts have been attributed²⁸ to human-induced climate change particularly through increased frequency and severity of extreme events. These include increased heat-related human mortality (*medium confidence*), warm-water coral bleaching and mortality (*high confidence*), and increased drought related tree mortality (*high confidence*). Observed increases in areas burned by wildfires have been attributed to human-induced climate change in some regions (*medium to high confidence*). Adverse impacts from tropical cyclones, with related losses and damages¹⁹, have increased due to sea level rise and the increase in heavy precipitation (*medium confidence*). Impacts in natural and human systems from slow-onset processes²⁹ such as ocean acidification, sea level rise or regional decreases in precipitation have also been attributed to human induced climate change (*high confidence*). {1.3, 2.3, 2.4, 2.5, 3.2, 3.4, 3.5, 3.6, 4.2, 5.2, 5.4, 5.6, 5.12, 7.2, 9.6, 9.8, 9.7, 9.8, 9.11, 11.3, Box 11.1, Box 11.2, Table 11.9, 12.3, 12.4, 13.3, 13.5, 13.10, 14.2, 14.5, 15.7, 15.8, 16.2, Box CCP5.1, CCP1.2, CCP2.2, CCP7.3, CCB EXTREME, CCB ILLNESS, CCB DISASTER, WGI 9, WGI 11.3-11.8, WGI SPM.3, SROCC Ch. 4}

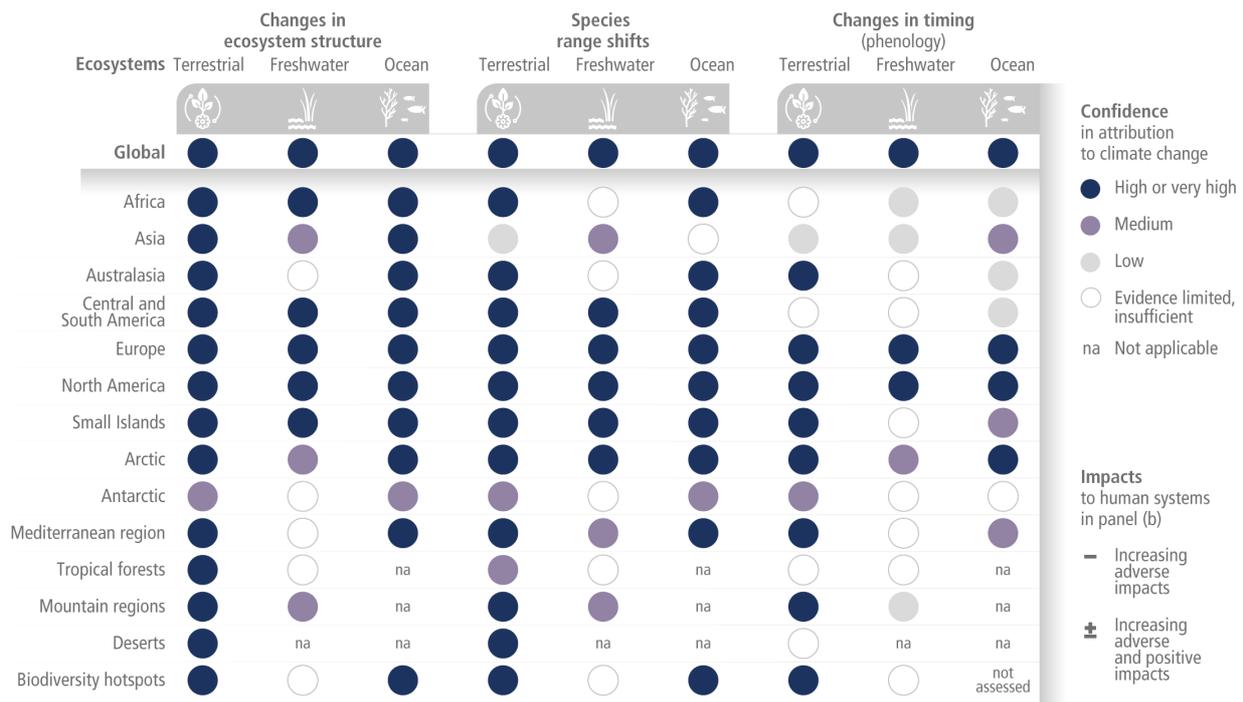
SPM.B.1.2 Climate change has caused substantial damages, and increasingly irreversible losses, in terrestrial, freshwater and coastal and open ocean marine ecosystems (*high confidence*). The extent and magnitude of climate change impacts are larger than estimated in previous assessments (*high confidence*). Widespread deterioration of ecosystem structure and function, resilience and natural adaptive capacity, as well as shifts in seasonal timing have occurred due to climate change (*high confidence*), with adverse socioeconomic consequences (*high confidence*). Approximately half of the species assessed globally have shifted polewards or, on land, also to higher elevations (*very high confidence*). Hundreds of local losses of species have been driven by increases in the magnitude of heat extremes (*high confidence*), as well as mass mortality events on land and in the ocean (*very high confidence*) and loss of kelp forests (*high confidence*). Some losses are already irreversible, such as the first species extinctions driven by climate change (*medium confidence*). Other impacts are approaching irreversibility such as the impacts of hydrological changes resulting from the retreat of glaciers, or the changes in some mountain (*medium confidence*) and Arctic ecosystems driven by permafrost thaw (*high confidence*). (Figure SPM.2a). {2.3, 2.4, 3.4, 3.5, 4.2, 4.3, 4.5, 9.6, 10.4, 11.3, 12.3, 12.8, 13.3, 13.4, 13.10, 14.4, 14.5, 14.6, 15.3, 16.2, CCP1.2; CCP3.2, CCP4.1, CCP5.2, CCP6.1, CCP6.2, CCP7.2, CCP7.3, CCP5.2, Figure CCP5.4, CCB PALEO, CCB EXTREMES, CCB ILLNESS, CCB SLR, CCB NATURAL, CCB MOVING PLATE, Figure TS.5, TS B1, SROCC 2.3}

²⁸ Attribution is defined as the process of evaluating the relative contributions of multiple causal factors to a change or event with an assessment of confidence. {Annex II Glossary, CWGB ATTRIB}

²⁹ Impacts of climate change are caused by slow onset and extreme events. Slow onset events are described among the climatic-impact drivers of the WGI AR6 and refer to the risks and impacts associated with e.g., increasing temperature means, desertification, decreasing precipitation, loss of biodiversity, land and forest degradation, glacial retreat and related impacts, ocean acidification, sea level rise and salinization (<https://interactive-atlas.ipcc.ch>).

Impacts of climate change are observed in many ecosystems and human systems worldwide

(a) Observed impacts of climate change on ecosystems



(b) Observed impacts of climate change on human systems

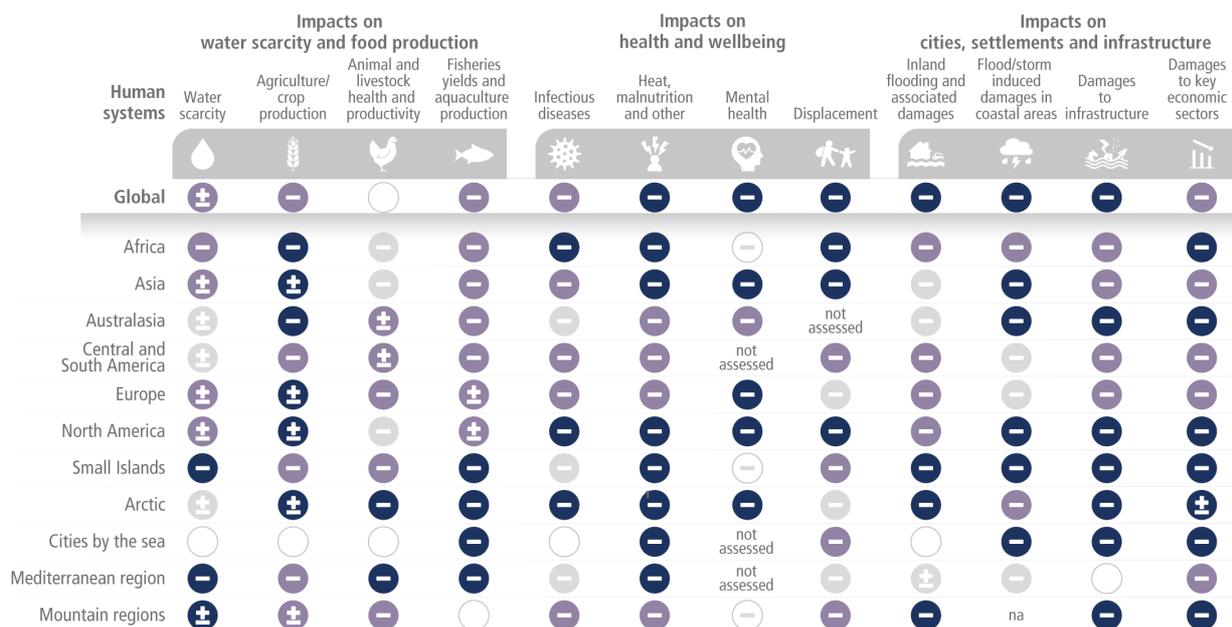


Figure SPM.2: Observed global and regional impacts on ecosystems and human systems attributed to climate change. Confidence levels reflect uncertainty in attribution of the observed impact to climate change. Global assessments focus on large studies, multi-species, meta-analyses and large reviews. For that reason they can be assessed with higher confidence than regional studies, which may often rely on smaller studies that have more limited data. Regional assessments consider evidence on impacts across an entire region and do not focus on any country in particular. (a) Climate change has already altered terrestrial, freshwater and ocean ecosystems at global scale, with multiple impacts evident at regional and local scales where there is sufficient literature to make an assessment. Impacts are evident on ecosystem structure, species geographic ranges and timing of seasonal life cycles (phenology) (for methodology and detailed references to chapters and cross-chapter papers see SMTS.1 and SMTS.1.1). (b) Climate change has already had diverse adverse impacts on human systems, including on water security and food production, health and well-being, and cities, settlements and infrastructure. The + and – symbols indicate the direction of observed impacts, with a – denoting

an increasing adverse impact and a \pm denoting that, within a region or globally, both adverse and positive impacts have been observed (e.g., adverse impacts in one area or food item may occur with positive impacts in another area or food item). Globally, ‘–’ denotes an overall adverse impact; ‘Water scarcity’ considers, e.g., water availability in general, groundwater, water quality, demand for water, drought in cities. Impacts on food production were assessed by excluding non-climatic drivers of production increases; Global assessment for agricultural production is based on the impacts on global aggregated production; ‘Reduced animal and livestock health and productivity’ considers, e.g., heat stress, diseases, productivity, mortality; ‘Reduced fisheries yields and aquaculture production’ includes marine and freshwater fisheries/production; ‘Infectious diseases’ include, e.g., water-borne and vector-borne diseases; ‘Heat, malnutrition and other’ considers, e.g., human heat-related morbidity and mortality, labour productivity, harm from wildfire, nutritional deficiencies; ‘Mental health’ includes impacts from extreme weather events, cumulative events, and vicarious or anticipatory events; ‘Displacement’ assessments refer to evidence of displacement attributable to climate and weather extremes; ‘Inland flooding and associated damages’ considers, e.g., river overflows, heavy rain, glacier outbursts, urban flooding; ‘Flood/storm induced damages in coastal areas’ include damages due to, e.g., cyclones, sea level rise, storm surges. Damages by key economic sectors are observed impacts related to an attributable mean or extreme climate hazard or directly attributed. Key economic sectors include standard classifications and sectors of importance to regions (for methodology and detailed references to chapters and cross-chapter papers see SMTS.1 and SMTS.1.2).

SPM.B.1.3 Climate change including increases in frequency and intensity of extremes have reduced food and water security, hindering efforts to meet Sustainable Development Goals (*high confidence*). Although overall agricultural productivity has increased, climate change has slowed this growth over the past 50 years globally (*medium confidence*), related negative impacts were mainly in mid- and low latitude regions but positive impacts occurred in some high latitude regions (*high confidence*). Ocean warming and ocean acidification have adversely affected food production from shellfish aquaculture and fisheries in some oceanic regions (*high confidence*). Increasing weather and climate extreme events have exposed millions of people to acute food insecurity³⁰ and reduced water security, with the largest impacts observed in many locations and/or communities in Africa, Asia, Central and South America, Small Islands and the Arctic (*high confidence*). Jointly, sudden losses of food production and access to food compounded by decreased diet diversity have increased malnutrition in many communities (*high confidence*), especially for Indigenous Peoples, small-scale food producers and low-income households (*high confidence*), with children, elderly people and pregnant women particularly impacted (*high confidence*). Roughly half of the world’s population currently experience severe water scarcity for at least some part of the year due to climatic and non-climatic drivers (*medium confidence*). (Figure SPM.2b) {3.5, Box 4.1, 4.3, 4.4, 5.2, 5.4, 5.8, 5.9, 5.12, 7.1, 7.2, 9.8, 10.4, 11.3, 12.3, 13.5, 14.4, 14.5, 15.3, 16.2, CCP5.2, CCP6.2}

SPM.B.1.4 Climate change has adversely affected physical health of people globally (*very high confidence*) and mental health of people in the assessed regions (*very high confidence*). Climate change impacts on health are mediated through natural and human systems, including economic and social conditions and disruptions (*high confidence*). In all regions extreme heat events have resulted in human mortality and morbidity (*very high confidence*). The occurrence of climate-related food-borne and water-borne diseases has increased (*very high confidence*). The incidence of vector-borne diseases has increased from range expansion and/or increased reproduction of disease vectors (*high confidence*). Animal and human diseases, including zoonoses, are emerging in new areas (*high confidence*). Water and food-borne disease risks have increased regionally from climate-sensitive aquatic pathogens, including *Vibrio* spp. (*high confidence*), and from toxic substances from harmful freshwater cyanobacteria (*medium confidence*). Although diarrheal diseases have decreased globally, higher temperatures, increased rain and flooding have increased the occurrence of diarrheal diseases, including cholera (*very high confidence*) and other gastrointestinal infections (*high confidence*). In assessed regions, some mental health challenges are associated with increasing temperatures (*high confidence*), trauma from weather and climate extreme events (*very high confidence*), and loss of livelihoods and culture (*high confidence*). Increased exposure to wildfire smoke, atmospheric dust, and aeroallergens have been associated with climate-sensitive cardiovascular and respiratory distress (*high confidence*). Health services have been disrupted by extreme events such as floods (*high confidence*). {4.3, 5.12, 7.2, Box 7.3, 8.2, 8.3, Figure 8.10,

³⁰ Acute food insecurity can occur at any time with a severity that threatens lives, livelihoods or both, regardless of the causes, context or duration, as a result of shocks risking determinants of food security and nutrition, and used to assess the need for humanitarian action (IPC Global Partners, 2019).

Box 8.6, 9.10, Figure 9.33, Figure 9.34, 10.4, 11.3, 12.3, 13.7, 14.4, 14.5, Figure 14.8, 15.3, 16.2, Table CCP5.1, CCP5.2.5, CCP6.2, Figure CCP6.3, Table CCB ILLNESS.1}

SPM.B.1.5 In urban settings, observed climate change has caused impacts on human health, livelihoods and key infrastructure (*high confidence*). Multiple climate and non-climate hazards impact cities, settlements and infrastructure and sometimes coincide, magnifying damage (*high confidence*). Hot extremes including heatwaves have intensified in cities (*high confidence*), where they have also aggravated air pollution events (*medium confidence*) and limited functioning of key infrastructure (*high confidence*). Observed impacts are concentrated amongst the economically and socially marginalized urban residents, e.g., in informal settlements (*high confidence*). Infrastructure, including transportation, water, sanitation and energy systems have been compromised by extreme and slow-onset events, with resulting economic losses, disruptions of services and impacts to wellbeing (*high confidence*). {4.3, 6.2, 7.1, 7.2, 9.9, 10.4, 11.3, 12.3, 13.6, 14.5, 15.3, CCP2.2, CCP4.2, CCP5.2}

SPM.B.1.6 Overall adverse economic impacts attributable to climate change, including slow-onset and extreme weather events, have been increasingly identified (*medium confidence*). Some positive economic effects have been identified in regions that have benefited from lower energy demand as well as comparative advantages in agricultural markets and tourism (*high confidence*). Economic damages from climate change have been detected in climate-exposed sectors, with regional effects to agriculture, forestry, fishery, energy, and tourism (*high confidence*), and through outdoor labour productivity (*high confidence*). Some extreme weather events, such as tropical cyclones, have reduced economic growth in the short-term (*high confidence*). Non-climatic factors including some patterns of settlement, and siting of infrastructure have contributed to the exposure of more assets to extreme climate hazards increasing the magnitude of the losses (*high confidence*). Individual livelihoods have been affected through changes in agricultural productivity, impacts on human health and food security, destruction of homes and infrastructure, and loss of property and income, with adverse effects on gender and social equity (*high confidence*). {3.5, 4.2, 5.12, 6.2, 7.2, 8.2, 9.6, 10.4, 13.10, 14.5, Box 14.6, 16.2, Table 16.5, 18.3, CCP6.2, CCB GENDER, CWGB ECONOMICS}

SPM.B.1.7 Climate change is contributing to humanitarian crises where climate hazards interact with high vulnerability (*high confidence*). Climate and weather extremes are increasingly driving displacement in all regions (*high confidence*), with small island states disproportionately affected (*high confidence*). Flood and drought-related acute food insecurity and malnutrition have increased in Africa (*high confidence*) and Central and South America (*high confidence*). While non-climatic factors are the dominant drivers of existing intrastate violent conflicts, in some assessed regions extreme weather and climate events have had a small, adverse impact on their length, severity or frequency, but the statistical association is weak (*medium confidence*). Through displacement and involuntary migration from extreme weather and climate events, climate change has generated and perpetuated vulnerability (*medium confidence*). {4.2, 4.3, 5.4, 7.2, 9.8, Box 9.9, Box 10.4, 12.3, 12.5, CCB MIGRATE, CCB DISASTER, 16.2}

Vulnerability and Exposure of Ecosystems and People

SPM.B.2 Vulnerability of ecosystems and people to climate change differs substantially among and within regions (*very high confidence*), driven by patterns of intersecting socio-economic development, unsustainable ocean and land use, inequity, marginalization, historical and ongoing patterns of inequity such as colonialism, and governance³¹ (*high confidence*). Approximately 3.3 to 3.6 billion people live in contexts that are highly vulnerable to climate change (*high confidence*). A high proportion of species is vulnerable to climate change (*high confidence*). Human and ecosystem vulnerability are interdependent (*high confidence*). Current unsustainable development patterns are increasing exposure of ecosystems and people to climate hazards (*high confidence*). {2.3, 2.4, 3.5, 4.3, 6.2, 8.2, 8.3, 9.4, 9.7, 10.4, 12.3, 14.5, 15.3, CCP5.2, CCP6.2, CCP7.3, CCP7.4, CCB GENDER}

³¹ Governance: The structures, processes and actions through which private and public actors interact to address societal goals. This includes formal and informal institutions and the associated norms, rules, laws and procedures for deciding, managing, implementing and monitoring policies and measures at any geographic or political scale, from global to local.

SPM.B.2.1 Since AR5 there is increasing evidence that degradation and destruction of ecosystems by humans increases the vulnerability of people (*high confidence*). Unsustainable land-use and land cover change, unsustainable use of natural resources, deforestation, loss of biodiversity, pollution, and their interactions, adversely affect the capacities of ecosystems, societies, communities and individuals to adapt to climate change (*high confidence*). Loss of ecosystems and their services has cascading and long-term impacts on people globally, especially for Indigenous Peoples and local communities who are directly dependent on ecosystems, to meet basic needs (*high confidence*). {2.3, 2.5, 2.6, 3.5, 3.6, 4.2, 4.3, 4.6, 5.1, 5.4, 5.5, 5.7, 5.8, 7.2, 8.1, 8.2, 8.3, 8.4, 8.5, 9.6, 10.4, 11.3, 12.2, 12.5, 13.8, 14.4, 14.5, 15.3, CCP1.2, CCP1.3, CCP2.2, CCP3, CCP4.3, CCP5.2, CCP6.2, CCP7.2, CCP7.3, CCP7.4, CCB ILLNESS, CCB MOVING PLATE, CCB SLR}

SPM.B.2.2 Non-climatic human-induced factors exacerbate current ecosystem vulnerability to climate change (*very high confidence*). Globally, and even within protected areas, unsustainable use of natural resources, habitat fragmentation, and ecosystem damage by pollutants increase ecosystem vulnerability to climate change (*high confidence*). Globally, less than 15% of the land, 21% of the freshwater and 8% of the ocean are protected areas. In most protected areas, there is insufficient stewardship to contribute to reducing damage from, or increasing resilience to, climate change (*high confidence*). {2.4, 2.5, 2.6, 3.4, 3.6, 4.2, 4.3, 5.8, 9.6, 11.3, 12.3, 13.3, 13.4, 14.5, 15.3, CCP1.2 Figure CCP1.15, CCP2.1, CCP2.2, CCP4.2, CCP5.2, CCP 6.2, CCP7.2, CCP7.3, CCB NATURAL}

SPM.B.2.3 Future vulnerability of ecosystems to climate change will be strongly influenced by the past, present and future development of human society, including from overall unsustainable consumption and production, and increasing demographic pressures, as well as persistent unsustainable use and management of land, ocean, and water (*high confidence*). Projected climate change, combined with non-climatic drivers, will cause loss and degradation of much of the world's forests (*high confidence*), coral reefs and low-lying coastal wetlands (*very high confidence*). While agricultural development contributes to food security, unsustainable agricultural expansion, driven in part by unbalanced diets³², increases ecosystem and human vulnerability and leads to competition for land and/or water resources (*high confidence*). {2.2, 2.3, 2.4, 2.6, 3.4, 3.5, 3.6, 4.3, 4.5, 5.6, 5.12, 5.13, 7.2, 12.3, 13.3, 13.4, 13.10, 14.5, CCP1.2, CCP2.2, CCP5.2, CCP6.2, CCP7.2, CCP7.3, CCB NATURAL, CCB HEALTH}

SPM.B.2.4 Regions and people with considerable development constraints have high vulnerability to climatic hazards (*high confidence*). Global hotspots of high human vulnerability are found particularly in West-, Central- and East Africa, South Asia, Central and South America, Small Island Developing States and the Arctic (*high confidence*). Vulnerability is higher in locations with poverty, governance challenges and limited access to basic services and resources, violent conflict and high levels of climate-sensitive livelihoods (e.g., smallholder farmers, pastoralists, fishing communities) (*high confidence*). Between 2010-2020, human mortality from floods, droughts and storms was 15 times higher in highly vulnerable regions, compared to regions with very low vulnerability (*high confidence*). Vulnerability at different spatial levels is exacerbated by inequity and marginalization linked to gender, ethnicity, low income or combinations thereof (*high confidence*), especially for many Indigenous Peoples and local communities (*high confidence*). Present development challenges causing high vulnerability are influenced by historical and ongoing patterns of inequity such as colonialism, especially for many Indigenous Peoples and local communities (*high confidence*). {4.2, 5.12, 6.2, 6.4, 7.1, 7.2, Box 7.1, 8.2, 8.3, Box 8.4, Figure 8.6, Box 9.1, 9.4, 9.7, 9.9, 10.3, 10.4, 10.6, 12.3, 12.5, Box 13.2, 14.4, 15.3, 15.6, 16.2, CCP6.2, CCP7.4}

SPM.B.2.5 Future human vulnerability will continue to concentrate where the capacities of local, municipal and national governments, communities and the private sector are least able to provide infrastructures and basic services (*high confidence*). Under the global trend of urbanization, human vulnerability will also concentrate in informal settlements and rapidly growing smaller settlements (*high confidence*). In rural areas vulnerability will be heightened by compounding processes including high emigration, reduced habitability and high reliance on climate-sensitive livelihoods (*high confidence*). Key infrastructure systems including sanitation, water, health, transport, communications and energy will be increasingly vulnerable if design

³² Balanced diets feature plant-based foods, such as those based on coarse grains, legumes fruits and vegetables, nuts and seeds, and animal-source foods produced in resilient, sustainable and low-greenhouse gas emissions systems, as described in SRCCL.

standards do not account for changing climate conditions (*high confidence*). Vulnerability will also rapidly rise in low-lying Small Island Developing States and atolls in the context of sea level rise and in some mountain regions, already characterised by high vulnerability due to high dependence on climate-sensitive livelihoods, rising population displacement, the accelerating loss of ecosystem services and limited adaptive capacities (*high confidence*). Future exposure to climatic hazards is also increasing globally due to socio-economic development trends including migration, growing inequality and urbanization (*high confidence*). {4.5, 5.5, 6.2, 7.2, 8.3, 9.9, 9.11, 10.3, 10.4, 12.3, 12.5, 13.6, 14.5, 15.3, 15.4, 16.5, CCP2.3, CCP4.3, CCP5.2, CCP5.3, CCP5.4, CCP6.2, CCB MIGRATE}

Risks in the near term (2021-2040)

SPM.B.3 Global warming, reaching 1.5°C in the near-term, would cause unavoidable increases in multiple climate hazards and present multiple risks to ecosystems and humans (*very high confidence*). The level of risk will depend on concurrent near-term trends in vulnerability, exposure, level of socioeconomic development and adaptation (*high confidence*). Near-term actions that limit global warming to close to 1.5°C would substantially reduce projected losses and damages related to climate change in human systems and ecosystems, compared to higher warming levels, but cannot eliminate them all (*very high confidence*). (Figure SPM.3, Box SPM.1) {WGI Table SPM.1, 16.4, 16.5, 16.6, CCP1.2, CCP5.3, CCB SLR, WGI SPM B1.3}

SPM.B.3.1 Near-term warming and increased frequency, severity and duration of extreme events will place many terrestrial, freshwater, coastal and marine ecosystems at high or very high risks of biodiversity loss (*medium to very high confidence*, depending on ecosystem). Near-term risks for biodiversity loss are moderate to high in forest ecosystems (*medium confidence*), kelp and seagrass ecosystems (*high to very high confidence*), and high to very high in Arctic sea-ice and terrestrial ecosystems (*high confidence*) and warm-water coral reefs (*very high confidence*). Continued and accelerating sea level rise will encroach on coastal settlements and infrastructure (*high confidence*) and commit low-lying coastal ecosystems to submergence and loss (*medium confidence*). If trends in urbanisation in exposed areas continue, this will exacerbate the impacts, with more challenges where energy, water and other services are constrained (*medium confidence*). The number of people at risk from climate change and associated loss of biodiversity will progressively increase (*medium confidence*). Violent conflict and, separately, migration patterns, in the near-term will be driven by socio-economic conditions and governance more than by climate change (*medium confidence*). (Figure SPM.3) {2.5, 3.4, 4.6, 6.2, 7.3, 8.7, 9.2, 9.9, 11.6, 12.5, 13.6, 13.10, 14.6, 15.3, 16.5, 16.6, CCP1.2, CCP2.1, CCP2.2, CCP5.3, CCP6.2, CCP6.3, CCB SLR, CCB MIGRATE}

SPM.B.3.2 In the near term, climate-associated risks to natural and human systems depend more strongly on changes in their vulnerability and exposure than on differences in climate hazards between emissions scenarios (*high confidence*). Regional differences exist, and risks are highest where species and people exist close to their upper thermal limits, along coastlines, in close association with ice or seasonal rivers (*high confidence*). Risks are also high where multiple non-climate drivers persist or where vulnerability is otherwise elevated (*high confidence*). Many of these risks are unavoidable in the near-term, irrespective of emission scenario (*high confidence*). Several risks can be moderated with adaptation (*high confidence*). (Figure SPM.3, Section C) {2.5, 3.3, 3.4, 4.5, 6.2, 7.1, 7.3, 8.2, 11.6, 12.4, 13.6, 13.7, 13.10, 14.5, 16.4, 16.5, CCP2.2, CCP4.3, CCP5.3, CCB SLR, WGI Table SPM.1}

SPM.B.3.3 Levels of risk for all Reasons for Concern (RFC) are assessed to become high to very high at lower global warming levels than in AR5 (*high confidence*). Between 1.2°C and 4.5°C global warming level very high risks emerge in all five RFCs compared to just two RFCs in AR5 (*high confidence*). Two of these transitions from high to very high risk are associated with near-term warming: risks to unique and threatened systems at a median value of 1.5°C [1.2 to 2.0] °C (*high confidence*) and risks associated with extreme weather events at a median value of 2°C [1.8 to 2.5] °C (*medium confidence*). Some key risks contributing to the RFCs are projected to lead to widespread, pervasive, and potentially irreversible impacts at global warming levels of 1.5–2°C if exposure and vulnerability are high and adaptation is low (*medium confidence*). Near-term actions that limit global warming to close to 1.5°C would substantially reduce projected losses and damages related to climate change in human systems and ecosystems, compared to higher warming levels, but cannot eliminate them all (*very high confidence*). (Figure SPM.3b) {16.5, 16.6, CCB SLR}

Mid to Long-term Risks (2041–2100)

SPM.B.4 Beyond 2040 and depending on the level of global warming, climate change will lead to numerous risks to natural and human systems (*high confidence*). For 127 identified key risks, assessed mid- and long-term impacts are up to multiple times higher than currently observed (*high confidence*). The magnitude and rate of climate change and associated risks depend strongly on near-term mitigation and adaptation actions, and projected adverse impacts and related losses and damages escalate with every increment of global warming (*very high confidence*). (Figure SPM.3) {2.5, 3.4, 4.4, 5.2, 6.2, 7.3, 8.4, 9.2, 10.2, 11.6, 12.4, 13.2, 13.3, 13.4, 13.5, 13.6, 13.7, 13.8, 14.6, 15.3, 16.5, 16.6, CCP1.2; CCP2.2, CCP3.3, CCP4.3, CCP5.3, CCP6.3, CCP7.3}

SPM.B.4.1 Biodiversity loss, and degradation, damages to and transformation of ecosystems are already key risks for every region due to past global warming and will continue to escalate with every increment of global warming (*very high confidence*). In terrestrial ecosystems, 3 to 14% of species assessed³³ will *likely* face very high risk of extinction³⁴ at global warming levels of 1.5°C, increasing up to 3 to 18% at 2°C, 3 to 29% at 3°C, 3 to 39% at 4°C, and 3 to 48% at 5°C. In ocean and coastal ecosystems, risk of biodiversity loss ranges between moderate and very high by 1.5°C global warming level and is moderate to very high by 2°C but with more ecosystems at high and very high risk (*high confidence*), and increases to high to very high across most ocean and coastal ecosystems by 3°C (*medium to high confidence*, depending on ecosystem). Very high extinction risk for endemic species in biodiversity hotspots is projected to at least double from 2% between 1.5°C and 2°C global warming levels and to increase at least tenfold if warming rises from 1.5°C to 3°C (*medium confidence*). (Figure SPM.3c, d, f) {2.4, 2.5, 3.4, 3.5, 12.3, 12.5, Table 12.6, 13.4, 13.10, 16.4, 16.6, CCP1.2, Figure CCP1.6; Figure CCP1.7, CCP5.3, CCP6.3, CCB PALEO}

SPM.B.4.2 Risks in physical water availability and water-related hazards will continue to increase by the mid- to long-term in all assessed regions, with greater risk at higher global warming levels (*high confidence*). At approximately 2°C global warming, snowmelt water availability for irrigation is projected to decline in some snowmelt dependent river basins by up to 20%, and global glacier mass loss of $18 \pm 13\%$ is projected to diminish water availability for agriculture, hydropower, and human settlements in the mid- to long-term, with these changes projected to double with 4°C global warming (*medium confidence*). In small islands, groundwater availability is threatened by climate change (*high confidence*). Changes to streamflow magnitude, timing and associated extremes are projected to adversely impact freshwater ecosystems in many watersheds by the mid- to long-term across all assessed scenarios (*medium confidence*). Projected increases in direct flood damages are higher by 1.4 to 2 times at 2°C and 2.5 to 3.9 times at 3°C compared to 1.5°C global warming without adaptation (*medium confidence*). At global warming of 4°C, approximately 10% of the global land area is projected to face increases in both extreme high and low river flows in the same location, with implications for planning for all water use sectors (*medium confidence*). Challenges for water management will be exacerbated in the near, mid and long term, depending on the magnitude, rate and regional details of future climate change and will be particularly challenging for regions with constrained resources for water management (*high confidence*). {2.3, Box 4.2, 4.4, 4.5, Figure 4.20, 15.3, CCB DISASTER, CCP5.3, SROCC 2.3}

SPM.B.4.3 Climate change will increasingly put pressure on food production and access, especially in vulnerable regions, undermining food security and nutrition (*high confidence*). Increases in frequency, intensity and severity of droughts, floods and heatwaves, and continued sea level rise will increase risks to food security (*high confidence*) in vulnerable regions from moderate to high between 1.5°C and 2°C global warming level, with no or low levels of adaptation (*medium confidence*). At 2°C or higher global warming level in the mid-term, food security risks due to climate change will be more severe, leading to malnutrition and micro-nutrient deficiencies, concentrated in Sub-Saharan Africa, South Asia, Central and South America and Small Islands (*high confidence*). Global warming will progressively weaken soil health and ecosystem

³³ Numbers of species assessed are in the tens of thousands globally.

³⁴ The term ‘very high risks of extinction’ is used here consistently with the IUCN categories and criteria and equates with ‘critically endangered’.

services such as pollination, increase pressure from pests and diseases, and reduce marine animal biomass, undermining food productivity in many regions on land and in the ocean (*medium confidence*). At 3°C or higher global warming level in the long term, areas exposed to climate-related hazards will expand substantially compared with 2°C or lower global warming level (*high confidence*), exacerbating regional disparity in food security risks (*high confidence*). (Figure SPM.3) {1.1, 3.3, CCB SLR, 4.5, 5.2, 5.4, 5.5, 5.8, 5.9, 5.12, CCB MOVING PLATE, 7.3, 8.3, 9.11,13.5,15.3, 16.5, 16.6}

SPM.B.4.4 Climate change and related extreme events will significantly increase ill health and premature deaths from the near- to long-term (*high confidence*). Globally, population exposure to heatwaves will continue to increase with additional warming, with strong geographical differences in heat-related mortality without additional adaptation (*very high confidence*). Climate-sensitive food-borne, water-borne, and vector-borne disease risks are projected to increase under all levels of warming without additional adaptation (*high confidence*). In particular, dengue risk will increase with longer seasons and a wider geographic distribution in Asia, Europe, Central and South America and sub-Saharan Africa, potentially putting additional billions of people at risk by the end of the century (*high confidence*). Mental health challenges, including anxiety and stress, are expected to increase under further global warming in all assessed regions, particularly for children, adolescents, elderly, and those with underlying health conditions (*very high confidence*). {4.5, 5.12, Box 5.10, 7.3, Fig 7.9, 8.4, 9.10, Fig 9.32, Fig 9.35, 10.4, Fig 10.11, 11.3, 12.3, Fig 12.5, Fig 12.6, 13.7, Fig 13.23, Fig 13.24, 14.5, 15.3, CCP6.2}

SPM.B.4.5 Climate change risks to cities, settlements and key infrastructure will rise rapidly in the mid- and long-term with further global warming, especially in places already exposed to high temperatures, along coastlines, or with high vulnerabilities (*high confidence*). Globally, population change in low-lying cities and settlements will lead to approximately a billion people projected to be at risk from coastal-specific climate hazards in the mid-term under all scenarios, including in Small Islands (*high confidence*). The population potentially exposed to a 100-year coastal flood is projected to increase by about 20% if global mean sea level rises by 0.15 m relative to 2020 levels; this exposed population doubles at a 0.75 m rise in mean sea level and triples at 1.4 m without population change and additional adaptation (*medium confidence*). Sea level rise poses an existential threat for some Small Islands and some low-lying coasts (*medium confidence*). By 2100 the value of global assets within the future 1-in-100 year coastal floodplains is projected to be between US\$7.9 and US\$12.7 trillion (2011 value) under RCP4.5, rising to between US\$8.8 and US\$14.2 trillion under RCP8.5 (*medium confidence*). Costs for maintenance and reconstruction of urban infrastructure, including building, transportation, and energy will increase with global warming level (*medium confidence*), the associated functional disruptions are projected to be substantial particularly for cities, settlements and infrastructure located on permafrost in cold regions and on coasts (*high confidence*). {6.2, 9.9, 10.4, 13.6, 13.10, 15.3, 16.5, CCP2.1, CCP2.2, CCP5.3, CCP6.2, CCB SLR, SROCC 2.3, SROCC CCB9}

SPM.B.4.6 Projected estimates of global aggregate net economic damages generally increase non-linearly with global warming levels (*high confidence*).³⁵ The wide range of global estimates, and the lack of comparability between methodologies, does not allow for identification of a robust range of estimates (*high confidence*). The existence of higher estimates than assessed in AR5 indicates that global aggregate economic impacts could be higher than previous estimates (*low confidence*).³⁶ Significant regional variation in aggregate economic damages from climate change is projected (*high confidence*) with estimated economic damages per capita for developing countries often higher as a fraction of income (*high confidence*). Economic damages, including both those represented and those not represented in economic markets, are projected to be lower at 1.5°C than at 3°C or higher global warming levels (*high confidence*). {4.4, 9.11, 11.5, 13.10, Box 14.6, 16.5, CWGB ECONOMICS}

SPM.B.4.7 In the mid- to long-term, displacement will increase with intensification of heavy precipitation and associated flooding, tropical cyclones, drought and, increasingly, sea level rise (*high confidence*). At progressive levels of warming, involuntary migration from regions with high exposure and low adaptive

³⁵ The assessment found estimated rates of increase in projected global economic damages that were both greater than linear and less than linear as global warming level increases. There is evidence that some regions could benefit from low levels of warming (*high confidence*). {CWGB ECONOMICS}

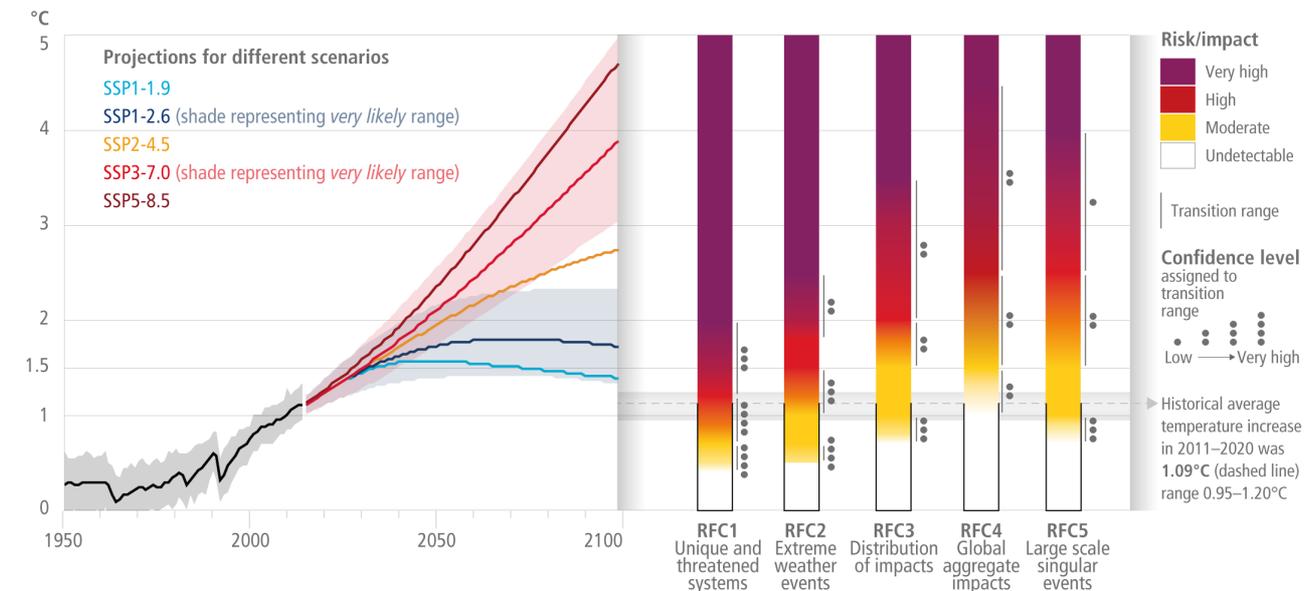
³⁶ *Low confidence* assigned due to the assessed lack of comparability and robustness of global aggregate economic damage estimates. {CWGB ECONOMICS}

capacity would occur (*medium confidence*). Compared to other socioeconomic factors the influence of climate on conflict is assessed as relatively weak (*high confidence*). Along long-term socioeconomic pathways that reduce non-climatic drivers, risk of violent conflict would decline (*medium confidence*). At higher global warming levels, impacts of weather and climate extremes, particularly drought, by increasing vulnerability will increasingly affect violent intrastate conflict (*medium confidence*). {7.3, 16.5, CCB MIGRATE, TSB7.4}

Global and regional risks for increasing levels of global warming

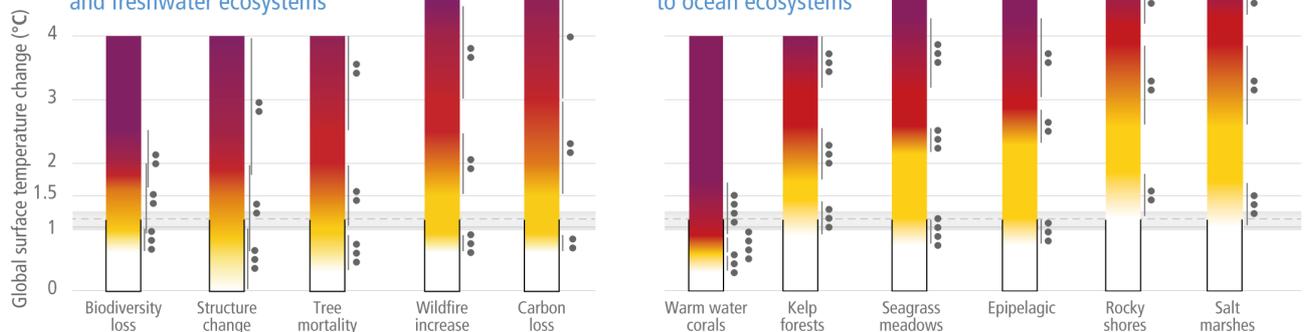
(a) Global surface temperature change
Increase relative to the period 1850–1900

(b) Reasons for Concern (RFC)
Impact and risk assessments assuming low to no adaptation

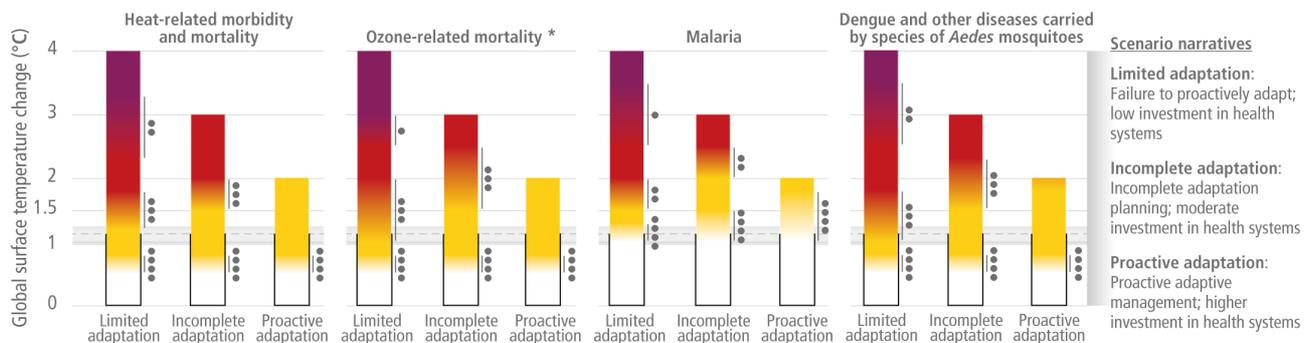


(c) Impacts and risks to terrestrial and freshwater ecosystems

(d) Impacts and risks to ocean ecosystems



(e) Climate sensitive health outcomes under three adaptation scenarios



* Mortality projections include demographic trends but do not include future efforts to improve air quality that reduce ozone concentrations.

(f) Examples of regional key risks

Absence of risk diagrams does not imply absence of risks within a region. The development of synthetic diagrams for Small Islands, Asia and Central and South America was limited due to the paucity of adequately downscaled climate projections, with uncertainty in the direction of change, the diversity of climatologies and socioeconomic contexts across countries within a region, and the resulting few numbers of impact and risk projections for different warming levels.

The risks listed are of at least *medium confidence* level:

- Small Islands**
 - Loss of terrestrial, marine and coastal biodiversity and ecosystem services
 - Loss of lives and assets, risk to food security and economic disruption due to destruction of settlements and infrastructure
 - Economic decline and livelihood failure of fisheries, agriculture, tourism and from biodiversity loss from traditional agroecosystems
 - Reduced habitability of reef and non-reef islands leading to increased displacement
 - Risk to water security in almost every small island
- North America**
 - Climate-sensitive mental health outcomes, human mortality and morbidity due to increasing average temperature, weather and climate extremes, and compound climate hazards
 - Risk of degradation of marine, coastal and terrestrial ecosystems, including loss of biodiversity, function, and protective services
 - Risk to freshwater resources with consequences for ecosystems, reduced surface water availability for irrigated agriculture, other human uses, and degraded water quality
 - Risk to food and nutritional security through changes in agriculture, livestock, hunting, fisheries, and aquaculture productivity and access
 - Risks to well-being, livelihoods and economic activities from cascading and compounding climate hazards, including risks to coastal cities, settlements and infrastructure from sea-level rise
- Europe**
 - Risks to people, economies and infrastructures due to coastal and inland flooding
 - Stress and mortality to people due to increasing temperatures and heat extremes
 - Marine and terrestrial ecosystems disruptions
 - Water scarcity to multiple interconnected sectors
 - Losses in crop production, due to compound heat and dry conditions, and extreme weather
- Central and South America**
 - Risk to water security
 - Severe health effects due to increasing epidemics, in particular vector-borne diseases
 - Coral reef ecosystems degradation due to coral bleaching
 - Risk to food security due to frequent/extreme droughts
 - Damages to life and infrastructure due to floods, landslides, sea level rise, storm surges and coastal erosion
- Australasia**
 - Degradation of tropical shallow coral reefs and associated biodiversity and ecosystem service values
 - Loss of human and natural systems in low-lying coastal areas due to sea-level rise
 - Impact on livelihoods and incomes due to decline in agricultural production
 - Increase in heat-related mortality and morbidity for people and wildlife
 - Loss of alpine biodiversity in Australia due to less snow
- Asia**
 - Urban infrastructure damage and impacts on human well-being and health due to flooding, especially in coastal cities and settlements
 - Biodiversity loss and habitat shifts as well as associated disruptions in dependent human systems across freshwater, land, and ocean ecosystems
 - More frequent, extensive coral bleaching and subsequent coral mortality induced by ocean warming and acidification, sea level rise, marine heat waves and resource extraction
 - Decline in coastal fishery resources due to sea level rise, decrease in precipitation in some parts and increase in temperature
 - Risk to food and water security due to increased temperature extremes, rainfall variability and drought
- Africa**
 - Species extinction and reduction or irreversible loss of ecosystems and their services, including freshwater, land and ocean ecosystems
 - Risk to food security, risk of malnutrition (micronutrient deficiency), and loss of livelihood due to reduced food production from crops, livestock and fisheries
 - Risks to marine ecosystem health and to livelihoods in coastal communities
 - Increased human mortality and morbidity due to increased heat and infectious diseases (including vector-borne and diarrhoeal diseases)
 - Reduced economic output and growth, and increased inequality and poverty rates
 - Increased risk to water and energy security due to drought and heat

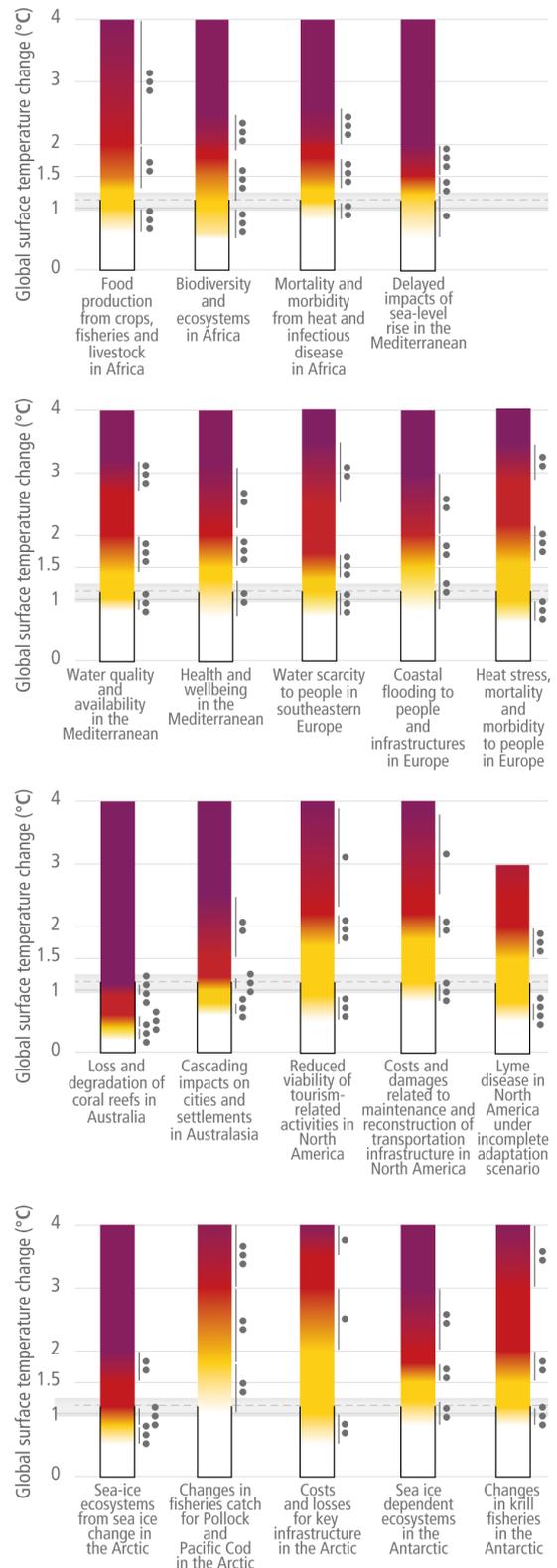


Figure SPM.3: Synthetic diagrams of global and sectoral assessments and examples of regional key risks. Diagrams show the change in the levels of impacts and risks assessed for global warming of 0-5°C global surface temperature change relative to pre-industrial period (1850-1900) over the range. (a) Global surface temperature changes in °C relative to 1850–1900. These changes were obtained by combining CMIP6 model simulations with observational constraints based on past simulated warming, as well as an updated assessment of equilibrium climate sensitivity (Box SPM.1). Changes relative to 1850–1900 based on 20-year averaging periods are calculated by adding 0.85°C (the observed global surface temperature increase from 1850–1900 to 1995–2014) to simulated changes relative to 1995–2014. *Very likely* ranges are shown for SSP1-2.6 and SSP3-

7.0 (WGI Figure SPM.8). Assessments were carried out at the global scale for (b), (c), (d) and (e). (b) The Reasons for Concern (RFC) framework communicates scientific understanding about accrual of risk for five broad categories. Diagrams are shown for each RFC, assuming low to no adaptation (i.e., adaptation is fragmented, localized and comprises incremental adjustments to existing practices). However, the transition to a very high risk level has an emphasis on irreversibility and adaptation limits. Undetectable risk level (white) indicates no associated impacts are detectable and attributable to climate change; moderate risk (yellow) indicates associated impacts are both detectable and attributable to climate change with at least *medium confidence*, also accounting for the other specific criteria for key risks; high risk (red) indicates severe and widespread impacts that are judged to be high on one or more criteria for assessing key risks; and very high risk level (purple) indicates very high risk of severe impacts and the presence of significant irreversibility or the persistence of climate-related hazards, combined with limited ability to adapt due to the nature of the hazard or impacts/risks. The horizontal line denotes the present global warming of 1.09°C which is used to separate the observed, past impacts below the line from the future projected risks above it. RFC1: Unique and threatened systems: ecological and human systems that have restricted geographic ranges constrained by climate-related conditions and have high endemism or other distinctive properties. Examples include coral reefs, the Arctic and its Indigenous Peoples, mountain glaciers and biodiversity hotspots. RFC2: Extreme weather events: risks/impacts to human health, livelihoods, assets and ecosystems from extreme weather events such as heatwaves, heavy rain, drought and associated wildfires, and coastal flooding. RFC3: Distribution of impacts: risks/impacts that disproportionately affect particular groups due to uneven distribution of physical climate change hazards, exposure or vulnerability. RFC4: Global aggregate impacts: impacts to socio-ecological systems that can be aggregated globally into a single metric, such as monetary damages, lives affected, species lost or ecosystem degradation at a global scale. RFC5: Large-scale singular events: relatively large, abrupt and sometimes irreversible changes in systems caused by global warming, such as ice sheet disintegration or thermohaline circulation slowing. Assessment methods are described in SM16.6 and are identical to AR5, but are enhanced by a structured approach to improve robustness and facilitate comparison between AR5 and AR6. Risks for (c) terrestrial and freshwater ecosystems and (d) ocean ecosystems. For c) and d), diagrams shown for each risk assume low to no adaptation. The transition to a very high risk level has an emphasis on irreversibility and adaptation limits. (e) Climate-sensitive human health outcomes under three scenarios of adaptation effectiveness. The assessed projections were based on a range of scenarios, including SRES, CMIP5, and ISIMIP, and, in some cases, demographic trends. The diagrams are truncated at the nearest whole °C within the range of temperature change in 2100 under three SSP scenarios in panel (a). (f) Examples of regional key risks. Risks identified are of at least *medium confidence* level. Key risks are identified based on the magnitude of adverse consequences (pervasiveness of the consequences, degree of change, irreversibility of consequences, potential for impact thresholds or tipping points, potential for cascading effects beyond system boundaries); likelihood of adverse consequences; temporal characteristics of the risk; and ability to respond to the risk, e.g., by adaptation. The full set of 127 assessed global and regional key risks is given in SM16.7. Diagrams are provided for some risks. The development of synthetic diagrams for Small Islands, Asia and Central and South America were limited by the availability of adequately downscaled climate projections, with uncertainty in the direction of change, the diversity of climatologies and socio-economic contexts across countries within a region, and the resulting low number of impact and risk projections for different warming levels. Absence of risks diagrams does not imply absence of risks within a region. (Box SPM.1) {16.5, 16.6, Figure 16.15, SM16.3, SM16.4, SM16.5, SM16.6 (methodologies), SM16.7, Figure 2.11, Figure SM3.1, Figure 7.9, Figure 9.6, Figure 11.6, Figure 13.28, Figure CCP6.5, Figure CCP4.8, Figure CCP4.10, Figure TS.4, WGI Figure SPM.8, WGI SPM A.1.2, Box SPM.1, WGI Ch. 2}

Complex, Compound and Cascading Risks

SPM.B.5 Climate change impacts and risks are becoming increasingly complex and more difficult to manage. Multiple climate hazards will occur simultaneously, and multiple climatic and non-climatic risks will interact, resulting in compounding overall risk and risks cascading across sectors and regions. Some responses to climate change result in new impacts and risks. (*high confidence*) {1.3, 2.4, Box 2.2, Box 9.5, 11.5, 13.5, 14.6, Box 15.1, CCP1.2, CCP2.2, CCB DISASTER, CCB INTERREG, CCB SRM, CCB COVID}

SPM.B.5.1 Concurrent and repeated climate hazards occur in all regions, increasing impacts and risks to health, ecosystems, infrastructure, livelihoods and food (*high confidence*). Multiple risks interact, generating new sources of vulnerability to climate hazards, and compounding overall risk (*high confidence*). Increasing concurrence of heat and drought events are causing crop production losses and tree mortality (*high confidence*). Above 1.5°C global warming increasing concurrent climate extremes will increase risk of simultaneous crop losses of maize in major food-producing regions, with this risk increasing further with higher global warming levels (*medium confidence*). Future sea level rise combined with storm surge and heavy rainfall will increase compound flood risks (*high confidence*). Risks to health and food production will be made more severe from the interaction of sudden food production losses from heat and drought, exacerbated by heat-induced labour productivity losses (*high confidence*). These interacting impacts will increase food prices, reduce household incomes, and lead to health risks of malnutrition and climate-related mortality with no or low levels of adaptation, especially in tropical regions (*high confidence*). Risks to food safety from climate change will further compound the risks to health by increasing food contamination of crops from mycotoxins and contamination of seafood from harmful algal blooms, mycotoxins, and chemical contaminants (*high confidence*). {5.2, 5.4, 5.8, 5.9, 5.11, 5.12, 7.2, 7.3, 9.8, 9.11, 10.4, 11.3, 11.5, 12.3, 13.5, 14.5, 15.3, Box 15.1, 16.6, CCP1.2, CCP6.2, Figure TS10C, WG1 SPM A.3.1, A.3.2 and C.2.7}

SPM.B.5.2 Adverse impacts from climate hazards and resulting risks are cascading across sectors and regions (*high confidence*), propagating impacts along coasts and urban centres (*medium confidence*) and in mountain regions (*high confidence*). These hazards and cascading risks also trigger tipping points in sensitive ecosystems and in significantly and rapidly changing social-ecological systems impacted by ice melt, permafrost thaw and changing hydrology in polar regions (*high confidence*). Wildfires, in many regions, have affected ecosystems and species, people and their built assets, economic activity, and health (*medium to high confidence*). In cities and settlements, climate impacts to key infrastructure are leading to losses and damages across water and food systems, and affect economic activity, with impacts extending beyond the area directly impacted by the climate hazard (*high confidence*). In Amazonia, and in some mountain regions, cascading impacts from climatic (e.g., heat) and non-climatic stressors (e.g., land use change) will result in irreversible and severe losses of ecosystem services and biodiversity at 2°C global warming level and beyond (*medium confidence*). Unavoidable sea level rise will bring cascading and compounding impacts resulting in losses of coastal ecosystems and ecosystem services, groundwater salinisation, flooding and damages to coastal infrastructure that cascade into risks to livelihoods, settlements, health, well-being, food and water security, and cultural values in the near to long-term (*high confidence*). (Figure SPM.3) {2.5, 3.4, 3.5, Box 7.3, Box 8.7, Box 9.4, Box 11.1, 11.5, 12.3, 13.9, 14.6, 15.3, 16.5, 16.6, CCP1.2, CCP2.2, CCP5.2, CCP5.3, CCP6.2, CCP6.3, Box CCP6.1, Box CCP6.2, CCB EXTREMES, Figure TS.10, WGI SPM Figure SPM.8d}

SPM.B.5.3 Weather and climate extremes are causing economic and societal impacts across national boundaries through supply-chains, markets, and natural resource flows, with increasing transboundary risks projected across the water, energy and food sectors (*high confidence*). Supply chains that rely on specialized commodities and key infrastructure can be disrupted by weather and climate extreme events. Climate change causes the redistribution of marine fish stocks, increasing risk of transboundary management conflicts among fisheries users, and negatively affecting equitable distribution of food provisioning services as fish stocks shift from lower to higher latitude regions, thereby increasing the need for climate-informed transboundary management and cooperation (*high confidence*). Precipitation and water availability changes increases the risk of planned infrastructure projects, such as hydropower in some regions, having reduced productivity for food and energy sectors including across countries that share river basins (*medium confidence*). {Figure TS.10e-f, 3.4, 3.5, 4.5, 5.8, 5.13, 6.2, 9.4, Box 9.5, 14.5, Box 14.5, Box 14.6, CCP5.3, CCB EXTREMES, CCB MOVING PLATE, CCB INTERREG, CCB DISASTER}

SPM B.5.4 Risks arise from some responses that are intended to reduce the risks of climate change, including risks from maladaptation and adverse side effects of some emission reduction and carbon dioxide removal measures (*high confidence*). Deployment of afforestation of naturally unforested land, or poorly implemented bioenergy, with or without carbon capture and storage, can compound climate-related risks to biodiversity, water and food security, and livelihoods, especially if implemented at large scales, especially in regions with insecure land tenure (*high confidence*). {Box 2.2, 4.1, 4.7, 5.13, Table 5.18, Box 9.3, Box 13.2, CCB NATURAL, CWGB BIOECONOMY}

SPM B.5.5 Solar radiation modification approaches, if they were to be implemented, introduce a widespread range of new risks to people and ecosystems, which are not well understood (*high confidence*). Solar radiation modification approaches have potential to offset warming and ameliorate some climate hazards, but substantial residual climate change or overcompensating change would occur at regional scales and seasonal timescales (*high confidence*). Large uncertainties and knowledge gaps are associated with the potential of solar radiation modification approaches to reduce climate change risks. Solar radiation modification would not stop atmospheric CO₂ concentrations from increasing or reduce resulting ocean acidification under continued anthropogenic emissions (*high confidence*). {XWGB SRM}

Impacts of Temporary Overshoot

SPM.B.6 If global warming transiently exceeds 1.5°C in the coming decades or later (overshoot)³⁷, then many human and natural systems will face additional severe risks, compared to remaining below 1.5°C (*high confidence*). Depending on the magnitude and duration of overshoot, some impacts will cause release of additional greenhouse gases (*medium confidence*) and some will be irreversible, even if global warming is reduced (*high confidence*). (Figure SPM.3) {2.5, 3.4, 12.3, 16.6, CCB SLR, CCB DEEP, Box SPM.1}

SPM.B.6.1 While model-based assessments of the impacts of overshoot pathways are limited, observations and current understanding of processes permit assessment of impacts from overshoot. Additional warming, e.g., above 1.5°C during an overshoot period this century, will result in irreversible impacts on certain ecosystems with low resilience, such as polar, mountain, and coastal ecosystems, impacted by ice-sheet, glacier melt, or by accelerating and higher committed sea level rise (*high confidence*).³⁸ Risks to human systems will increase, including those to infrastructure, low-lying coastal settlements, some ecosystem-based adaptation measures, and associated livelihoods (*high confidence*), cultural and spiritual values (*medium confidence*). Projected impacts are less severe with shorter duration and lower levels of overshoot (*medium confidence*). {2.5, 3.4, 12.3, 13.2, 16.5, 16.6, CCP 1.2, CCP5.3, CCP6.1, CCP6.2, CCP2.2, CCB SLR, Box TS4, SROCC 2.3, SROCC 5.4, WG1 SPM B5 and C3}

SPM.B.6.2 Risk of severe impacts increase with every additional increment of global warming during overshoot (*high confidence*). In high-carbon ecosystems (currently storing 3,000 to 4,000 GtC)³⁹ such impacts are already observed and are projected to increase with every additional increment of global warming, such as increased wildfires, mass mortality of trees, drying of peatlands, and thawing of permafrost, weakening natural land carbon sinks and increasing releases of greenhouse gases (*medium confidence*). The resulting contribution to a potential amplification of global warming indicates that a return to a given global warming level or below would be more challenging (*medium confidence*). {2.4, 2.5, CCP4.2, WG1 SPM B.4.3, SROCC 5.4}

SPM.C: Adaptation Measures and Enabling Conditions

Adaptation, in response to current climate change, is reducing climate risks and vulnerability mostly via adjustment of existing systems. Many adaptation options exist and are used to help manage projected climate change impacts, but their implementation depends upon the capacity and effectiveness of governance and decision-making processes. These and other enabling conditions can also support Climate Resilient Development (Section D).

Current Adaptation and its Benefits

³⁷ In this report, overshoot pathways exceed 1.5°C global warming and then return to that level, or below, after several decades.

³⁸ Despite limited evidence specifically on the impacts of a temporary overshoot of 1.5°C, a much broader evidence base from process understanding and the impacts of higher global warming levels allows a high confidence statement on the irreversibility of some impacts that would be incurred following such an overshoot.

³⁹ At the global scale, terrestrial ecosystems currently remove more carbon from the atmosphere (-3.4 ± 0.9 Gt yr⁻¹) than they emit ($+1.6 \pm 0.7$ Gt yr⁻¹), a net sink of -1.9 ± 1.1 Gt yr⁻¹. However, recent climate change has shifted some systems in some regions from being net carbon sinks to net carbon sources.

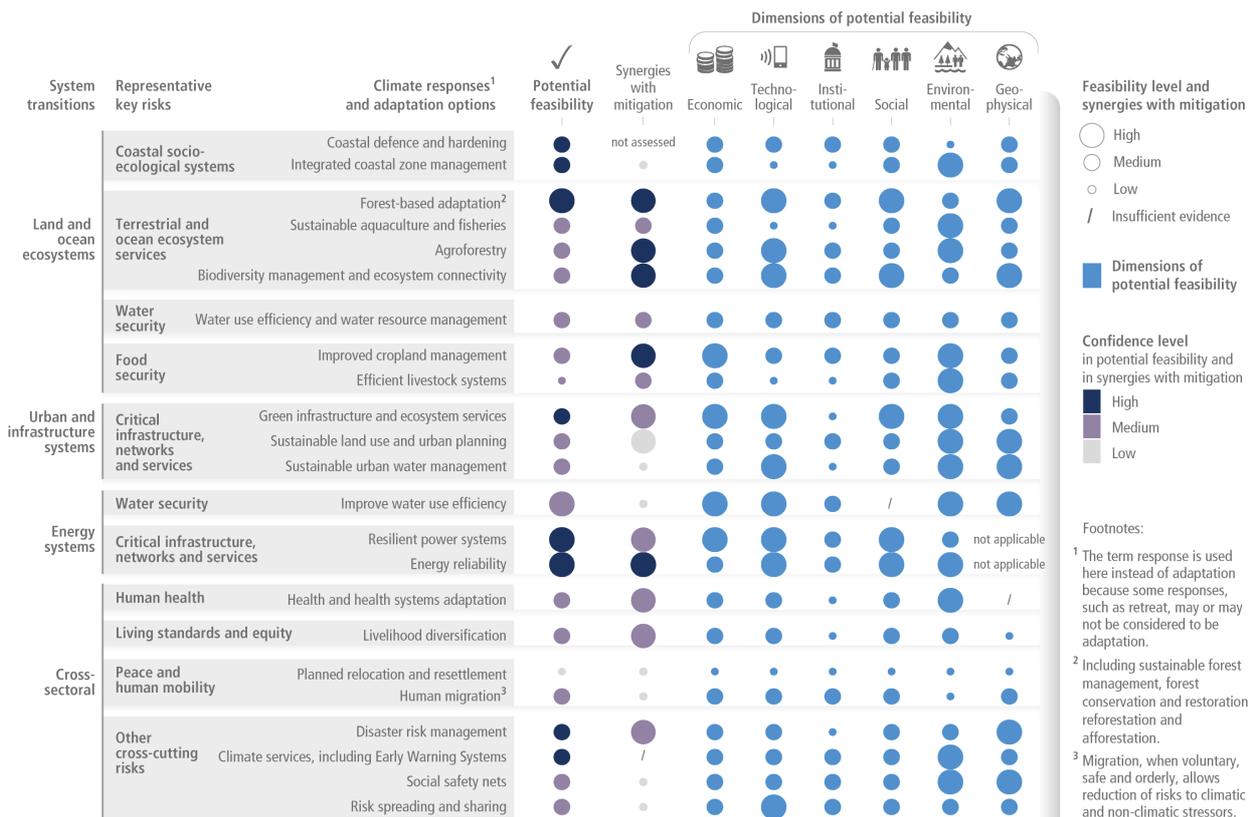
SPM.C.1 Progress in adaptation planning and implementation has been observed across all sectors and regions, generating multiple benefits (*very high confidence*). However, adaptation progress is unevenly distributed with observed adaptation gaps⁴⁰ (*high confidence*). Many initiatives prioritize immediate and near-term climate risk reduction which reduces the opportunity for transformational adaptation (*high confidence*). {2.6, 5.14, 7.4, 10.4, 12.5, 13.11, 14.7, 16.3, 17.3, CCP5.2, CCP5.4}

SPM.C.1.1 Adaptation planning and implementation have continued to increase across all regions (*very high confidence*). Growing public and political awareness of climate impacts and risks has resulted in at least 170 countries and many cities including adaptation in their climate policies and planning processes (*high confidence*). Decision support tools and climate services are increasingly being used (*very high confidence*). Pilot projects and local experiments are being implemented in different sectors (*high confidence*). Adaptation can generate multiple additional benefits such as improving agricultural productivity, innovation, health and well-being, food security, livelihood, and biodiversity conservation as well as reduction of risks and damages (*very high confidence*). {1.4, CCB ADAPT, 2.6, CCB NATURE, 3.5, 3.6, 4.7, 4.8, 5.4, 5.6, 5.10, 6.4.2, 7.4, 8.5, 9.3, 9.6, 10.4, 12.5, 13.11, 15.5, 16.3, 17.2, 17.3, 17.5 CCP5.4}

SPM.C.1.2 Despite progress, adaptation gaps exist between current levels of adaptation and levels needed to respond to impacts and reduce climate risks (*high confidence*). Most observed adaptation is fragmented, small in scale, incremental, sector-specific, designed to respond to current impacts or near-term risks, and focused more on planning rather than implementation (*high confidence*). Observed adaptation is unequally distributed across regions (*high confidence*), and gaps are partially driven by widening disparities between the estimated costs of adaptation and documented finance allocated to adaptation (*high confidence*). The largest adaptation gaps exist among lower income population groups (*high confidence*). At current rates of adaptation planning and implementation the adaptation gap will continue to grow (*high confidence*). As adaptation options often have long implementation times, long-term planning and accelerated implementation, particularly in the next decade, is important to close adaptation gaps, recognising that constraints remain for some regions (*high confidence*). {1.1, 1.4, 5.6, 6.3, Figure 6.4, 7.4, 8.3, 10.4, 11.3, 11.7, 15.2, Box 13.1, 13.11, 15.5, Box16.1, Figure 16.4, Figure 16.5, 16.3, 16.5, 17.4, 18.2, CCP2.4, CCP5.4, CCB FINANCE, CCB SLR}

⁴⁰ Adaptation gaps are defined as the difference between actually implemented adaptation and a societally set goal, determined largely by preferences related to tolerated climate change impacts and reflecting resource limitations and competing priorities.

Diverse feasible climate responses and adaptation options exist to respond to Representative Key Risks of climate change, with varying synergies with mitigation
 Multidimensional feasibility and synergies with mitigation of climate responses and adaptation options relevant in the near-term, at global scale and up to 1.5°C of global warming



Climate responses and adaptation options have benefits for ecosystems, ethnic groups, gender equity, low-income groups and the Sustainable Development Goals
 Relations of sectors and groups at risk (as observed) and the SDGs (relevant in the near-term, at global scale and up to 1.5°C of global warming) with climate responses and adaptation options

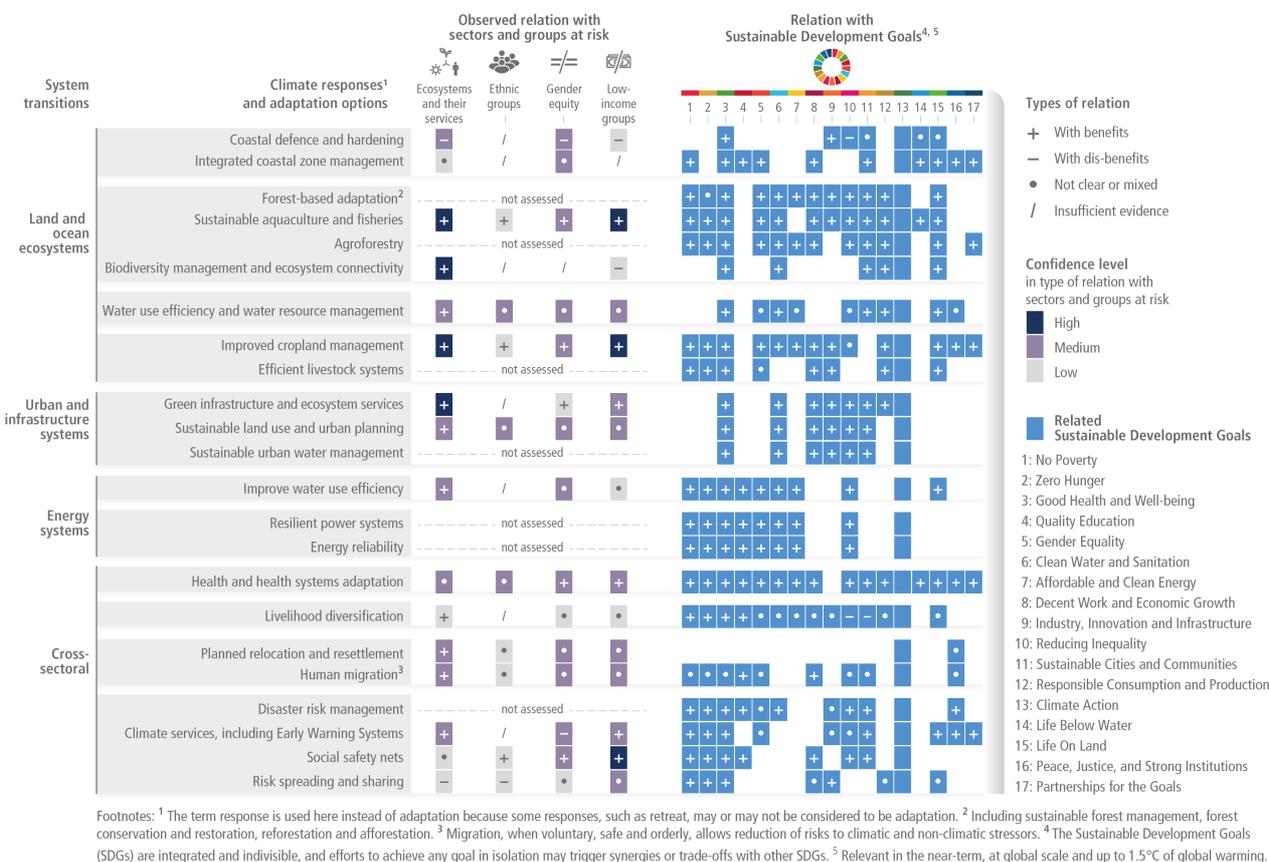


Figure SPM.4: (a) Climate responses and adaptation options, organized by System Transitions and Representative Key Risks (RKR), are assessed for their multidimensional feasibility at global scale, in the near term and up to 1.5°C global

warming. As literature above 1.5°C is limited, feasibility at higher levels of warming may change, which is currently not possible to assess robustly. Climate responses and adaptation options at global scale are drawn from a set of options assessed in AR6 that have robust evidence across the feasibility dimensions. This figure shows the six feasibility dimensions (economic, technological, institutional, social, environmental and geophysical) that are used to calculate the potential feasibility of climate responses and adaptation options, along with their synergies with mitigation. For potential feasibility and feasibility dimensions, the figure shows high, medium, or low feasibility. Synergies with mitigation are identified as high, medium, and low. Insufficient evidence is denoted by a dash. {CCB FEASIB., Table SMCCB FEASIB.1.1; SR1.5 4.SM.4.3}

Figure SPM.4: (b) Climate responses and adaptation options, organized by System Transitions and Representative Key Risks, are assessed at global scale for their likely ability to reduce risks for ecosystems and social groups at risk, as well as their relation with the 17 Sustainable Development Goals (SDGs). Climate responses and adaptation options are assessed for observed benefits (+) to ecosystems and their services, ethnic groups, gender equity, and low-income groups, or observed dis-benefits (-) for these systems and groups. Where there is highly diverging evidence of benefits/ dis-benefits across the scientific literature, e.g., based on differences between regions, it is shown as not clear or mixed (•). Insufficient evidence is shown by a dash. The relation with the SDGs is assessed as having benefits (+), dis-benefits (-) or not clear or mixed (•) based on the impacts of the climate response and adaptation option on each SDG. Areas not coloured indicate there is no evidence of a relation or no interaction with the respective SDG. The climate responses and adaptation options are drawn from two assessments. For comparability of climate responses and adaptation options see Table SM17.5. {17.2, 17.5; CCB FEASIB}

Future Adaptation Options and their Feasibility

SPM.C.2 There are feasible⁴¹ and effective⁴² adaptation options which can reduce risks to people and nature. The feasibility of implementing adaptation options in the near-term differs across sectors and regions (*very high confidence*). The effectiveness of adaptation to reduce climate risk is documented for specific contexts, sectors and regions (*high confidence*) and will decrease with increasing warming (*high confidence*). Integrated, multi-sectoral solutions that address social inequities, differentiate responses based on climate risk and cut across systems, increase the feasibility and effectiveness of adaptation in multiple sectors (*high confidence*). (Figure SPM.4) {Figure TS.6e, 1.4, 3.6, 4.7, 5.12, 6.3, 7.4, 11.3, 11.7, 13.2, 15.5, 17.6, CCB FEASIB, CCP2.3}

Land, Ocean and Ecosystems Transition

SPM.C.2.1 Adaptation to water-related risks and impacts make up the majority of all documented adaptation (*high confidence*). For inland flooding, combinations of non-structural measures like early warning systems and structural measures like levees have reduced loss of lives (*medium confidence*). Enhancing natural water retention such as by restoring wetlands and rivers, land use planning such as no build zones or upstream forest management, can further reduce flood risk (*medium confidence*). On-farm water management, water storage, soil moisture conservation and irrigation are some of the most common adaptation responses and provide economic, institutional or ecological benefits and reduce vulnerability (*high confidence*). Irrigation is effective in reducing drought risk and climate impacts in many regions and has several livelihood benefits, but needs appropriate management to avoid potential adverse outcomes, which can include accelerated depletion of groundwater and other water sources and increased soil salinization (*medium confidence*). Large scale irrigation can also alter local to regional temperature and precipitation patterns (*high confidence*), including both alleviating and exacerbating temperature extremes (*medium confidence*). The effectiveness of most water-related adaptation options to reduce projected risks declines with increasing warming (*high confidence*). {4.1,

⁴¹ In this report, feasibility refers to the potential for a mitigation or adaptation option to be implemented. Factors influencing feasibility are context-dependent, temporally dynamic, and may vary between different groups and actors. Feasibility depends on geophysical, environmental-ecological, technological, economic, socio-cultural and institutional factors that enable or constrain the implementation of an option. The feasibility of options may change when different options are combined and increase when enabling conditions are strengthened.

⁴² Effectiveness refers to the extent to which an adaptation option is anticipated or observed to reduce climate-related risk.

4.6, 4.7, Box 4.3, Box 4.6, Box 4.7, Figure 4.28, Figure 4.29, Table 4.9, 9.3, 9.7, 11.3, 12.5, 13.1, 13.2, 16.3, CCP5.4, Figure 4.22}

SPM.C.2.2 Effective adaptation options, together with supportive public policies enhance food availability and stability and reduce climate risk for food systems while increasing their sustainability (*medium confidence*). Effective options include cultivar improvements, agroforestry, community-based adaptation, farm and landscape diversification, and urban agriculture (*high confidence*). Institutional feasibility, adaptation limits of crops and cost effectiveness also influence the effectiveness of the adaptation options (*limited evidence, medium agreement*). Agroecological principles and practices, ecosystem-based management in fisheries and aquaculture, and other approaches that work with natural processes support food security, nutrition, health and well-being, livelihoods and biodiversity, sustainability and ecosystem services (*high confidence*). These services include pest control, pollination, buffering of temperature extremes, and carbon sequestration and storage (*high confidence*). Trade-offs and barriers associated with such approaches include costs of establishment, access to inputs and viable markets, new knowledge and management (*high confidence*) and their potential effectiveness varies by socio-economic context, ecosystem zone, species combinations and institutional support (*medium confidence*). Integrated, multi-sectoral solutions that address social inequities and differentiate responses based on climate risk and local situation will enhance food security and nutrition (*high confidence*). Adaptation strategies which reduce food loss and waste or support balanced diets³³ (as described in the IPCC Special Report on Climate Change and Land) contribute to nutrition, health, biodiversity and other environmental benefits (*high confidence*). {3.2, 4.7, 4.6, Box 4.3, 5.4, 5.5, 5.6, 5.8, 5.9, 5.10, 5.11, 5.12, 5.13, 5.14, 7.4, Box 5.10, Box 5.13, 6.3, 10.4, 12.5, 13.5, 13.10, 14.5, CWGB BIOECONOMY, CCB MOVING PLATE, CCB NATURAL, CCB FEASIB, CCP5.4, CCB HEALTH}

SPM.C.2.3 Adaptation for natural forests⁴³ includes conservation, protection and restoration measures. In managed forests⁴⁴, adaptation options include sustainable forest management, diversifying and adjusting tree species compositions to build resilience, and managing increased risks from pests and diseases and wildfires. Restoring natural forests and drained peatlands and improving sustainability of managed forests, generally enhances the resilience of carbon stocks and sinks. Cooperation, and inclusive decision making, with local communities and Indigenous Peoples, as well as recognition of inherent rights of Indigenous Peoples, is integral to successful forest adaptation in many areas. (*high confidence*) {2.6, Box 2.2, CCB NATURAL, CCB FEASIB, CCB INDIG, 5.6, 5.13, 11.4, 12.5, 13.5, Box 14.1, Box 14.2, Table 5.23, Box CCP7.1, CCP7.5}.

SPM.C.2.4 Conservation, protection and restoration of terrestrial, freshwater, coastal and ocean ecosystems, together with targeted management to adapt to unavoidable impacts of climate change, reduces the vulnerability of biodiversity to climate change (*high confidence*). The resilience of species, biological communities and ecosystem processes increases with size of natural area, by restoration of degraded areas and by reducing non-climatic stressors (*high confidence*). To be effective, conservation and restoration actions will increasingly need to be responsive, as appropriate, to ongoing changes at various scales, and plan for future changes in ecosystem structure, community composition and species' distributions, especially as 1.5°C global warming is approached and even more so if it is exceeded (*high confidence*). Adaptation options, where circumstances allow, include facilitating the movement of species to new ecologically appropriate locations, particularly through increasing connectivity between conserved or protected areas, targeted intensive management for vulnerable species and protecting refugial areas where species can survive locally (*medium confidence*). {2.3, Figure 2.1, 2.6, Table 2.6, 2.6, 3.6, Box 3.4, 4.6, Box 11.2, 12.3, 12.5, 3.3, 13.4, 14.7, Box 4.6, CCP5.4, CCB FEASIB}

SPM.C.2.5 Effective Ecosystem-based Adaptation⁴⁴ reduces a range of climate change risks to people, biodiversity and ecosystem services with multiple co-benefits (*high confidence*). Ecosystem-based Adaptation

⁴³ In this report, the term natural forests describes those which are subject to little or no direct human intervention, whereas the term managed forests describes those where planting or other management activities take place, including those managed for commodity production.

⁴⁴ Ecosystem based Adaptation (EbA) is recognised internationally under the Convention on Biological Diversity (CBD14/5). A related concept is Nature-based Solutions (NbS), which includes a broader range of approaches with safeguards, including those that contribute to adaptation and mitigation. The term 'Nature-based Solutions' is widely but not universally used in the scientific literature. The term is the subject of ongoing debate, with concerns that it may lead to the misunderstanding that NbS on its own can provide a global solution to climate change.

is vulnerable to climate change impacts, with effectiveness declining with increasing global warming (*high confidence*). Urban greening using trees and other vegetation can provide local cooling (*very high confidence*). Natural river systems, wetlands and upstream forest ecosystems reduce flood risk by storing water and slowing water flow, in most circumstances (*high confidence*). Coastal wetlands protect against coastal erosion and flooding associated with storms and sea level rise where sufficient space and adequate habitats are available until rates of sea level rise exceeds natural adaptive capacity to build sediment (*very high confidence*). {2.4, 2.5, 2.6, Table 2.7, 3.4, 3.5, 3.6, Figure 3.26, 4.6, Box 4.6, Box 4.7, 5.5, 5.14, Box 5.11, 6.3, 6.4, Figure 6.6, 7.4, 8.5, 8.6, 9.6, 9.8, 9.9, 10.2, 11.3, 12.5, 13.3, 13.4, 13.5, 14.5, Box 14.7, 16.3, 18.3, CCB HEALTH, CCB NATURAL, CCB MOVING PLATE, CCB FEASIB.3, CWGB BIOECONOMY, CCP5.4}

Urban, Rural and Infrastructure Transition

SPM.C.2.6 Considering climate change impacts and risks in the design and planning of urban and rural settlements and infrastructure is critical for resilience and enhancing human well-being (*high confidence*). The urgent provision of basic services, infrastructure, livelihood diversification and employment, strengthening of local and regional food systems and community-based adaptation enhance lives and livelihoods, particularly of low-income and marginalised groups (*high confidence*). Inclusive, integrated and long-term planning at local, municipal, sub-national and national scales, together with effective regulation and monitoring systems and financial and technological resources and capabilities foster urban and rural system transition (*high confidence*). Effective partnerships between governments, civil society, and private sector organizations, across scales provide infrastructure and services in ways that enhance the adaptive capacity of vulnerable people (*medium to high confidence*). {5.12, 5.13, 5.14, Box 6.3, 6.3, 6.4, Box 6.6, Table 6.6, 7.4, 12.5, 13.6, 14.5, Box14.4, Box17.4, CCB FEASIB, CCP2.3, CCP2.4, CCP5.4}

SPM.C.2.7 An increasing number of adaptation responses exist for urban systems, but their feasibility and effectiveness is constrained by institutional, financial, and technological access and capacity, and depends on coordinated and contextually appropriate responses across physical, natural and social infrastructure (*high confidence*). Globally, more financing is directed at physical infrastructure than natural and social infrastructure (*medium confidence*) and there is *limited evidence* of investment in the informal settlements hosting the most vulnerable urban residents (*medium to high confidence*). Ecosystem-based adaptation (e.g., urban agriculture and forestry, river restoration) has increasingly been applied in urban areas (*high confidence*). Combined ecosystem-based and structural adaptation responses are being developed, and there is growing evidence of their potential to reduce adaptation costs and contribute to flood control, sanitation, water resources management, landslide prevention and coastal protection (*medium confidence*). {3.6, Box 4.6, 5.12, 6.3, 6.4, Table 6.8, 7.4, 9.7, 9.9, 10.4, Table 10.3, 11.3, 11.7, Box 11.6, 12.5, 13.2, 13.3, 13.6, 14.5, 15.5, 17.2, Box 17.4, CCB FEASIB, CCP2.3, CCP 3.2, CCP5.4, CCB SLR, SROCC ES}

SPM C.2.8: Sea level rise poses a distinctive and severe adaptation challenge as it implies dealing with slow onset changes and increased frequency and magnitude of extreme sea level events which will escalate in the coming decades (*high confidence*). Such adaptation challenges would occur much earlier under high rates of sea level rise, in particular if low-likelihood, high impact outcomes associated with collapsing ice sheets occur (*high confidence*). Responses to ongoing sea level rise and land subsidence in low-lying coastal cities and settlements and small islands include protection, accommodation, advance and planned relocation (*high confidence*)⁴⁵. These responses are more effective if combined and/or sequenced, planned well ahead, aligned with sociocultural values and development priorities, and underpinned by inclusive community engagement processes (*high confidence*). {CCB SLR, CCP2.3, 6.2, 10.4, 11.7, Box 11.6, 13.2.2, 14.5.9.2, 15.5, SROCC ES: C3.2, WGI SPM B5, C3}

SPM.C.2.9 Approximately 3.4 billion people globally live in rural areas around the world, and many are highly vulnerable to climate change. Integrating climate adaptation into social protection programs, including cash transfers and public works programmes, is highly feasible and increases resilience to climate change, especially when supported by basic services and infrastructure. Social safety nets are increasingly being reconfigured to build adaptive capacities of the most vulnerable in rural and also urban communities. Social

⁴⁵ The term 'response' is used here instead of adaptation because some responses, such as retreat, may or may not be considered to be adaptation.

safety nets that support climate change adaptation have strong co-benefits with development goals such as education, poverty alleviation, gender inclusion and food security. (*high confidence*) {5.14, 9.4, 9.10, 9.11, 12.5, 14.5, CCB GENDER, CCB FEASIB, CCP5.4}

Energy System Transition

SPM.C.2.10 Within energy system transitions, the most feasible adaptation options support infrastructure resilience, reliable power systems and efficient water use for existing and new energy generation systems (*very high confidence*). Energy generation diversification, including with renewable energy resources and generation that can be decentralised depending on context (e.g., wind, solar, small scale hydroelectric) and demand side management (e.g., storage, and energy efficiency improvements) can reduce vulnerabilities to climate change, especially in rural populations (*high confidence*). Adaptations for hydropower and thermo-electric power generation are effective in most regions up to 1.5°C to 2°C, with decreasing effectiveness at higher levels of warming (*medium confidence*). Climate responsive energy markets, updated design standards on energy assets according to current and projected climate change, smart-grid technologies, robust transmission systems and improved capacity to respond to supply deficits have high feasibility in the medium- to long-term, with mitigation co-benefits (*very high confidence*). {4.6, 4.7, Figure 4.28, Figure 4.29, 10.4, Table 11.8, Figure 13.19, Figure 13.16, 13.6, 18.3, CCB FEASIB, CWGB BIOECONOMY, CCP5.2, CCP5.4}

Cross-cutting Options

SPM.C.2.11 Strengthening the climate resiliency of health systems will protect and promote human health and wellbeing (*high confidence*). There are multiple opportunities for targeted investments and finance to protect against exposure to climate hazards, particularly for those at highest risk. Heat Health Action Plans that include early warning and response systems are effective adaptation options for extreme heat (*high confidence*). Effective adaptation options for water-borne and food-borne diseases include improving access to potable water, reducing exposure of water and sanitation systems to flooding and extreme weather events, and improved early warning systems (*very high confidence*). For vector-borne diseases, effective adaptation options include surveillance, early warning systems, and vaccine development (*very high confidence*). Effective adaptation options for reducing mental health risks under climate change include improving surveillance, access to mental health care, and monitoring of psychosocial impacts from extreme weather events (*high confidence*). Health and well-being would benefit from integrated adaptation approaches that mainstream health into food, livelihoods, social protection, infrastructure, water and sanitation policies requiring collaboration and coordination at all scales of governance (*very high confidence*). {5.12, 6.3, 7.4, 9.10, Box 9.7, 11.3, 12.5, 13.7, 14.5, CCB FEASIB, CCB ILLNESS, CCB COVID}

SPM.C.2.12 Increasing adaptive capacities minimises the negative impacts of climate-related displacement and involuntary migration for migrants and sending and receiving areas (*high confidence*). This improves the degree of choice under which migration decisions are made, ensuring safe and orderly movements of people within and between countries (*high confidence*). Some development reduces underlying vulnerabilities associated with conflict, and adaptation contributes by reducing the impacts of climate change on climate sensitive drivers of conflict (*high confidence*). Risks to peace are reduced, for example, by supporting people in climate-sensitive economic activities (*medium confidence*) and advancing women's empowerment (*high confidence*). {7.4, 12.5, CCB MIGRATE, Box 9.8, Box 10.2, CCB FEASIB}

SPM.C.2.13 There are a range of adaptation options, such as disaster risk management, early warning systems, climate services and risk spreading and sharing that have broad applicability across sectors and provide greater benefits to other adaptation options when combined (*high confidence*). For example, climate services that are inclusive of different users and providers can improve agricultural practices, inform better water use and efficiency, and enable resilient infrastructure planning (*high confidence*). {2.6, 3.6, 4.7, 5.4, 5.5, 5.6, 5.8, 5.9, 5.12, 5.14, 9.4, 9.8, 10.4, 12.5, 13.11, CCB MOVING PLATE, CCB FEASIB, CCP5.4}

Limits to Adaptation

SPM.C.3 Soft limits to some human adaptation have been reached, but can be overcome by addressing a range of constraints, primarily financial, governance, institutional and policy constraints (*high confidence*). Hard

limits to adaptation have been reached in some ecosystems (*high confidence*). With increasing global warming, losses and damages will increase and additional human and natural systems will reach adaptation limits (*high confidence*). {Figure TS.7, 1.4, 2.4, 2.5, 2.6, CCB SLR, 3.4, 3.6, 4.7, Figure 4.30, 5.5, Table 8.6, Box 10.7, 11.7, Table 11.16, 12.5, 13.2, 13.5, 13.6, 13.10, 13.11, Figure 13.21, 14.5, 15.6, 16.4, Figure 16.8, Table 16.3, Table 16.4, CCP1.2, CCP1.3, CCP2.3, CCP3.3, CCP5.2, CCP5.4, CCP6.3, CCP7.3}

SPM.C.3.1 Soft limits to some human adaptation have been reached, but can be overcome by addressing a range of constraints, which primarily consist of financial, governance, institutional and policy constraints (*high confidence*). For example, individuals and households in low lying coastal areas in Australasia and Small Islands and smallholder farmers in Central and South America, Africa, Europe and Asia have reached soft limits (*medium confidence*). Inequity and poverty also constrain adaptation, leading to soft limits and resulting in disproportionate exposure and impacts for most vulnerable groups (*high confidence*). Lack of climate literacy⁴⁶ at all levels and limited availability of information and data pose further constraints to adaptation planning and implementation (*medium confidence*). {1.4, 4.7, 5.4, Table 8.6, 8.4, 9.1, 9.4, 9.5, 9.8, 11.7, 12.5, 13.5, 15.3, 15.5, 15.6, 16.4, Figure 16.8, 16.4, Box 16.1, CCP5.2, CCP5.4, CCP6.3}

SPM.C.3.2 Financial constraints are important determinants of soft limits to adaptation across sectors and all regions (*high confidence*). Although global tracked climate finance has shown an upward trend since AR5, current global financial flows for adaptation, including from public and private finance sources, are insufficient for and constrain implementation of adaptation options especially in developing countries (*high confidence*). The overwhelming majority of global tracked climate finance was targeted to mitigation while a small proportion was targeted to adaptation (*very high confidence*). Adaptation finance has come predominantly from public sources (*very high confidence*). Adverse climate impacts can reduce the availability of financial resources by incurring losses and damages and through impeding national economic growth, thereby further increasing financial constraints for adaptation, particularly for developing and least developed countries (*medium confidence*). {1.4, 2.6, 3.6, 4.7, Figure 4.30, 5.14, 7.4, Table 8.6, 8.4, 9.4, 9.9, 9.11, 10.5, 12.5, 13.3, 13.11, Box 14.4, 15.6, 16.2, 16.4, Figure 16.8, Table 16.4, 17.4, 18.1, CCB FINANCE, CCP2.4, CCP5.4, CCP6.3, Figure TS 7}

SPM.C.3.3 Many natural systems are near the hard limits of their natural adaptation capacity and additional systems will reach limits with increasing global warming (*high confidence*). Ecosystems already reaching or surpassing hard adaptation limits include some warm water coral reefs, some coastal wetlands, some rainforests, and some polar and mountain ecosystems (*high confidence*). Above 1.5°C global warming level, some ecosystem-based adaptation measures will lose their effectiveness in providing benefits to people as these ecosystems will reach hard adaptation limits (*high confidence*). {1.4, 2.4, 2.6, 3.4, 3.6, CCB SLR, 9.6, Box 11.2, 13.4, 14.5, 15.5, 16.4, 16.6, 17.2, CCP1.2, CCP5.2, CCP6.3, CCP7.3, Figure SPM.4}

SPM.3.4 In human systems, some coastal settlements face soft adaptation limits due to technical and financial difficulties of implementing coastal protection (*high confidence*). Above 1.5°C global warming level, limited freshwater resources pose potential hard limits for Small Islands and for regions dependent on glacier and snow-melt (*medium confidence*). By 2°C global warming level, soft limits are projected for multiple staple crops in many growing areas, particularly in tropical regions (*high confidence*). By 3°C global warming level, soft limits are projected for some water management measures for many regions, with hard limits projected for parts of Europe (*medium confidence*). Transitioning from incremental to transformational adaptation can help overcome soft adaptation limits (*high confidence*). {1.4, 4.7, 5.4, 5.8, 7.2, 7.3, 8.4, Table 8.6, 9.8, 10.4, 12.5, 13.2, 13.6, 16.4, 17.2, CCB SLR, CCP1.3, Box CCP1.1, CCP2.3, CCP3.3, CCP4.4, CCP5.3}

SPM.C.3.5 Adaptation does not prevent all losses and damages, even with effective adaptation and before reaching soft and hard limits. Losses and damages are unequally distributed across systems, regions and sectors and are not comprehensively addressed by current financial, governance and institutional arrangements, particularly in vulnerable developing countries. With increasing global warming, losses and damages increase and become increasingly difficult to avoid, while strongly concentrated among the poorest vulnerable

⁴⁶ Climate literacy encompasses being aware of climate change, its anthropogenic causes and implications.

populations. (*high confidence*) {1.4, 2.6, 3.4, 3.6, 6.3, Figure 6.4, 8.4, 13.7, 13.2, 13.10, 17.2, CCB LOSS, CCB SLR, CCP2.3, CCP4.4, CWGB ECONOMIC}

Avoiding Maladaptation

SPM.C.4 There is increased evidence of maladaptation¹⁵ across many sectors and regions since the AR5. Maladaptive responses to climate change can create lock-ins of vulnerability, exposure and risks that are difficult and expensive to change and exacerbate existing inequalities. Maladaptation can be avoided by flexible, multi-sectoral, inclusive and long-term planning and implementation of adaptation actions with benefits to many sectors and systems. (*high confidence*) {1.3, 1.4, 2.6., Box 2.2, 3.2, 3.6, Box 4.3, Box 4.5, 4.6, 4.7, Figure 4.29, 5.6, 5.13, 8.2, 8.3, 8.4, 8.6, 9.6, 9.7, 9.8, 9.9, 9.10, 9.11, Box 9.5, Box 9.8, Box 9.9, Box 11.6, 13.11, 13.3, 13.4, 13.5, 14.5, 15.5, 15.6, 16.3, 17.3, 17.4, 17.6, 17.2, 17.5, CCP5.4, CCB NATURAL, CCB SLR, CCB DEEP, CWGB BIOECONOMY, CCP2.3, CCP2.3}

SPM.C.4.1 Actions that focus on sectors and risks in isolation and on short-term gains often lead to maladaptation if long-term impacts of the adaptation option and long-term adaptation commitment are not taken into account (*high confidence*). The implementation of these maladaptive actions can result in infrastructure and institutions that are inflexible and/or expensive to change (*high confidence*). For example, seawalls effectively reduce impacts to people and assets in the short-term but can also result in lock-ins and increase exposure to climate risks in the long-term unless they are integrated into a long-term adaptive plan (*high confidence*). Adaptation integrated with development reduces lock-ins and creates opportunities (e.g., infrastructure upgrading) (*medium confidence*). {1.4, 3.4, 3.6, 10.4, 11.7, Box 11.6, 13.2, 17.2, 17.5, 17.6, CCP 2.3, CCB SLR, CCB DEEP}

SPM.C.4.2 Biodiversity and ecosystem resilience to climate change are decreased by maladaptive actions, which also constrain ecosystem services. Examples of these maladaptive actions for ecosystems include fire suppression in naturally fire-adapted ecosystems or hard defences against flooding. These actions reduce space for natural processes and represent a severe form of maladaptation for the ecosystems they degrade, replace or fragment, thereby reducing their resilience to climate change and the ability to provide ecosystem services for adaptation. Considering biodiversity and autonomous adaptation in long-term planning processes reduces the risk of maladaptation. (*high confidence*) {2.4, 2.6, Table 2.7, 3.4, 3.6, 4.7, 5.6, 5.13, Table 5.21, 5.13, Box 13.2, 17.2, 17.5, Table 5.23, Box 11.2, 13.2, CCP5.4}

SPM.C.4.3 Maladaptation especially affects marginalised and vulnerable groups adversely (e.g., Indigenous Peoples, ethnic minorities, low-income households, informal settlements), reinforcing and entrenching existing inequities. Adaptation planning and implementation that do not consider adverse outcomes for different groups can lead to maladaptation, increasing exposure to risks, marginalising people from certain socio-economic or livelihood groups, and exacerbating inequity. Inclusive planning initiatives informed by cultural values, Indigenous knowledge, local knowledge, and scientific knowledge can help prevent maladaptation. (*high confidence*) (Figure SPM.4) {2.6, 3.6, 4.3, 4.6, 4.8, 5.12, 5.13, 5.14, 6.1, Box 7.1, 8.4, 11.4, 12.5, Box 13.2, 14.4, Box 14.1, 17.2, 17.5, 18.2, 17.2., CCP2.4}

SPM.C.4.4 To minimize maladaptation, multi-sectoral, multi-actor and inclusive planning with flexible pathways encourages low-regret⁴⁷ and timely actions that keep options open, ensure benefits in multiple sectors and systems and indicate the available solution space for adapting to long-term climate change (*very high confidence*). Maladaptation is also minimized by planning that accounts for the time it takes to adapt (*high confidence*), the uncertainty about the rate and magnitude of climate risk (*medium confidence*) and a wide range of potentially adverse consequences of adaptation actions (*high confidence*). {1.4, 3.6, 5.12, 5.13, 5.14, 11.6, 11.7, 17.3, 17.6, CCP2.3, CCP2.4, CCB SLR, CCB DEEP; CCP5.4}

⁴⁷ From AR5, an option that would generate net social and/or economic benefits under current climate change and a range of future climate change scenarios, and represent one example of robust strategies.

Enabling Conditions

SPM.C.5 Enabling conditions are key for implementing, accelerating and sustaining adaptation in human systems and ecosystems. These include political commitment and follow-through, institutional frameworks, policies and instruments with clear goals and priorities, enhanced knowledge on impacts and solutions, mobilization of and access to adequate financial resources, monitoring and evaluation, and inclusive governance processes. (*high confidence*) {1.4, 2.6, 3.6, 4.8, 6.4, 7.4, 8.5, 9.4, 10.5, 11.4, 11.7, 12.5, 13.11, 14.7, 15.6, 17.4, 18.4, CCB INDIG, CCB FINANCE, CCP2.4, CCP5.4}

SPM.C.5.1 Political commitment and follow-through across all levels of government accelerate the implementation of adaptation actions (*high confidence*). Implementing actions can require large upfront investments of human, financial and technological resources (*high confidence*), whilst some benefits could only become visible in the next decade or beyond (*medium confidence*). Accelerating commitment and follow-through is promoted by rising public awareness, building business cases for adaptation, accountability and transparency mechanisms, monitoring and evaluation of adaptation progress, social movements, and climate-related litigation in some regions (*medium confidence*). {3.6, 4.8, 5.8, 6.4, 8.5, 9.4, 11.7, 12.5, 13.11, 17.4, 17.5, 18.4, CCB COVID, CCP2.4}

SPM.C.5.2 Institutional frameworks, policies and instruments that set clear adaptation goals and define responsibilities and commitments and that are coordinated amongst actors and governance levels, strengthen and sustain adaptation actions (*very high confidence*). Sustained adaptation actions are strengthened by mainstreaming adaptation into institutional budget and policy planning cycles, statutory planning, monitoring and evaluation frameworks and into recovery efforts from disaster events (*high confidence*). Instruments that incorporate adaptation such as policy and legal frameworks, behavioural incentives, and economic instruments that address market failures, such as climate risk disclosure, inclusive and deliberative processes strengthen adaptation actions by public and private actors (*medium confidence*). {1.4, 3.6, 4.8, 5.14, 6.3, 6.4, 7.4, 9.4, 10.4, 11.7, Box 11.6, Table 11.17, 13.10, 13.11, 14.7, 15.6, 17.3, 17.4, 17.5, 17.6, 18.4, CCB DEEP, CCP2.4, CCP5.4, CCP6.3}

SPM.C.5.3 Enhancing knowledge on risks, impacts, and their consequences, and available adaptation options promotes societal and policy responses (*high confidence*). A wide range of top-down, bottom-up and co-produced processes and sources can deepen climate knowledge and sharing, including capacity building at all scales, educational and information programmes, using the arts, participatory modelling and climate services, Indigenous knowledge and local knowledge and citizen science (*high confidence*). These measures can facilitate awareness, heighten risk perception and influence behaviours (*high confidence*). {1.3, 3.6, 4.8, 5.9, 5.14, 6.4, Table 6.8, 7.4, 9.4, 10.5, 11.1, 11.7, 12.5, 13.9, 13.11, 14.3, 15.6, 15.6, 17.4, 18.4, CCB INDIG, CCP2.4.1}.

SPM.C.5.4 With adaptation finance needs estimated to be higher than those presented in AR5, enhanced mobilization of and access to financial resources are essential for implementation of adaptation and to reduce adaptation gaps (*high confidence*). Building capacity and removing some barriers to accessing finance is fundamental to accelerate adaptation, especially for vulnerable groups, regions and sectors (*high confidence*). Public and private finance instruments include inter alia grants, guarantee, equity, concessional debt, market debt, and internal budget allocation as well as savings in households and insurance. Public finance is an important enabler of adaptation (*high confidence*). Public mechanisms and finance can leverage private sector finance for adaptation by addressing real and perceived regulatory, cost and market barriers, for example via public-private partnerships (*high confidence*). Financial and technological resources enable effective and ongoing implementation of adaptation, especially when supported by institutions with a strong understanding of adaptation needs and capacity (*high confidence*). {4.8, 5.14, 6.4, Table 6.10, 7.4, 9.4, Table 11.17, 12.5, 13.11, 15.6, 17.4, 18.4, BOX 18.9, CCP5.4, CCB FINANCE}.

SPM.C.5.5 Monitoring and evaluation (M&E) of adaptation are critical for tracking progress and enabling effective adaptation (*high confidence*). M&E implementation is currently limited (*high confidence*) but has increased since AR5 at local and national levels. Although most of the monitoring of adaptation is focused towards planning and implementation, the monitoring of outcomes is critical for tracking the effectiveness and

progress of adaptation (*high confidence*). M&E facilitates learning on successful and effective adaptation measures, and signals when and where additional action may be needed. M&E systems are most effective when supported by capacities and resources and embedded in enabling governance systems (*high confidence*). {1.4, 2.6, 6.4, 7.4, 11.7, 11.8, 13.2, 13.11, 17.5, 18.4, CCB PROGRESS, CCB NATURAL, CCB ILLNESS, CCB DEEP, CCP2.4}.

SPM.C.5.6 Inclusive governance that prioritises equity and justice in adaptation planning and implementation leads to more effective and sustainable adaptation outcomes (*high confidence*). Vulnerabilities and climate risks are often reduced through carefully designed and implemented laws, policies, processes, and interventions that address context specific inequities such as based on gender, ethnicity, disability, age, location and income (*high confidence*). These approaches, which include multi-stakeholder co-learning platforms, transboundary collaborations, community-based adaptation and participatory scenario planning, focus on capacity-building, and meaningful participation of the most vulnerable and marginalised groups, and their access to key resources to adapt (*high confidence*). {1.4, 2.6, 3.6, 4.8, 5.4, 5.8, 5.9, 5.13, 6.4, 7.4, 8.5, 11.8, 12.5, 13.11, 14.7, 15.5, 15.7, 17.3, 17.5, 18.4, CCB HEALTH, CCB GENDER, CCB INDIG, CCP2.4, CCP5.4, CCP6.4}

SPM.D: Climate Resilient Development

Climate Resilient Development integrates adaptation measures and their enabling conditions (Section C) with mitigation to advance sustainable development for all. Climate resilient development involves questions of equity and system transitions in land, ocean and ecosystems; urban and infrastructure; energy; industry; and society and includes adaptations for human, ecosystem and planetary health. Pursuing climate resilient development focuses on both where people and ecosystems are co-located as well as the protection and maintenance of ecosystem function at the planetary scale. Pathways for advancing climate resilient development are development trajectories that successfully integrate mitigation and adaptation actions to advance sustainable development. Climate resilient development pathways may be temporarily coincident with any RCP and SSP scenario used throughout AR6, but do not follow any particular scenario in all places and over all time.

Conditions for Climate Resilient Development

SPM.D.1 Evidence of observed impacts, projected risks, levels and trends in vulnerability, and adaptation limits, demonstrate that worldwide climate resilient development action is more urgent than previously assessed in AR5. Comprehensive, effective, and innovative responses can harness synergies and reduce trade-offs between adaptation and mitigation to advance sustainable development. (*very high confidence*) {2.6, 3.4, 3.6, 4.2, 4.6, 7.2, 7.4, 8.3, 8.4, 9.3, 10.6, 13.3, 13.8, 13.10, 14.7, 17.2, 18.3, Figure 18.1, Table 18.5, Box 18.1}

SPM.D.1.1 There is a rapidly narrowing window of opportunity to enable climate resilient development. Multiple climate resilient development pathways are still possible by which communities, the private sector, governments, nations and the world can pursue climate resilient development – each involving and resulting from different societal choices influenced by different contexts and opportunities and constraints on system transitions. Climate resilient development pathways are progressively constrained by every increment of warming, in particular beyond 1.5°C, social and economic inequalities, the balance between adaptation and mitigation varying by national, regional and local circumstances and geographies, according to capabilities including resources, vulnerability, culture and values, past development choices leading to past emissions and future warming scenarios, bounding the climate resilient development pathways remaining, and the ways in which development trajectories are shaped by equity, and social and climate justice. (*very high confidence*) {2.6, 4.7, 4.8, 5.14, 6.4, 7.4, 8.3, 9.4, 9.3, 9.4, 9.5, 10.6, 11.8, 12.5, 13.10, 14.7, 15.3, 18.5, CCP2.3, CCP3.4, CCP4.4, CCP5.3, CCP5.4, Table CCP5.2, CCP6.3, CCP7.5, Figure TS14.d}

SPM.D.1.2 Opportunities for climate resilient development are not equitably distributed around the world (*very high confidence*). Climate impacts and risks exacerbate vulnerability and social and economic inequities and consequently increase persistent and acute development challenges, especially in developing regions and sub-regions, and in particularly exposed sites, including coasts, small islands, deserts, mountains and polar regions. This in turn undermines efforts to achieve sustainable development, particularly for vulnerable and marginalized communities (*very high confidence*). {2.5, 4.4, 4.7, 6.3, 9.4, Box 6.4, Figure 6.5, Table 18.5, CWGB URBAN, CCB HEALTH, CCP2.2, CCP3.2, CCP3.3, CCP5.4, CCP6.2}

SPM.D.1.3 Embedding effective and equitable adaptation and mitigation in development planning can reduce vulnerability, conserve and restore ecosystems, and enable climate resilient development. This is especially challenging in localities with persistent development gaps and limited resources (*high confidence*). Dynamic trade-offs and competing priorities exist between mitigation, adaptation, and development. Integrated and inclusive system-oriented solutions based on equity and social and climate justice reduce risks and enable climate resilient development (*high confidence*). {1.4, 2.6, 3.6, 4.7, 4.8, Box 4.5, Box 4.8, 5.13, 7.4, 8.5, 9.4, 10.6, Box 9.3, Box 2.2, 12.5, 12.6, 13.3, 13.4, 13.10, 13.11, 14.7, 18.4, CCB HEALTH, SRCCL, CCB DEEP, CCP2, CCP5.4}

There is a rapidly narrowing window of opportunity to enable climate resilient development

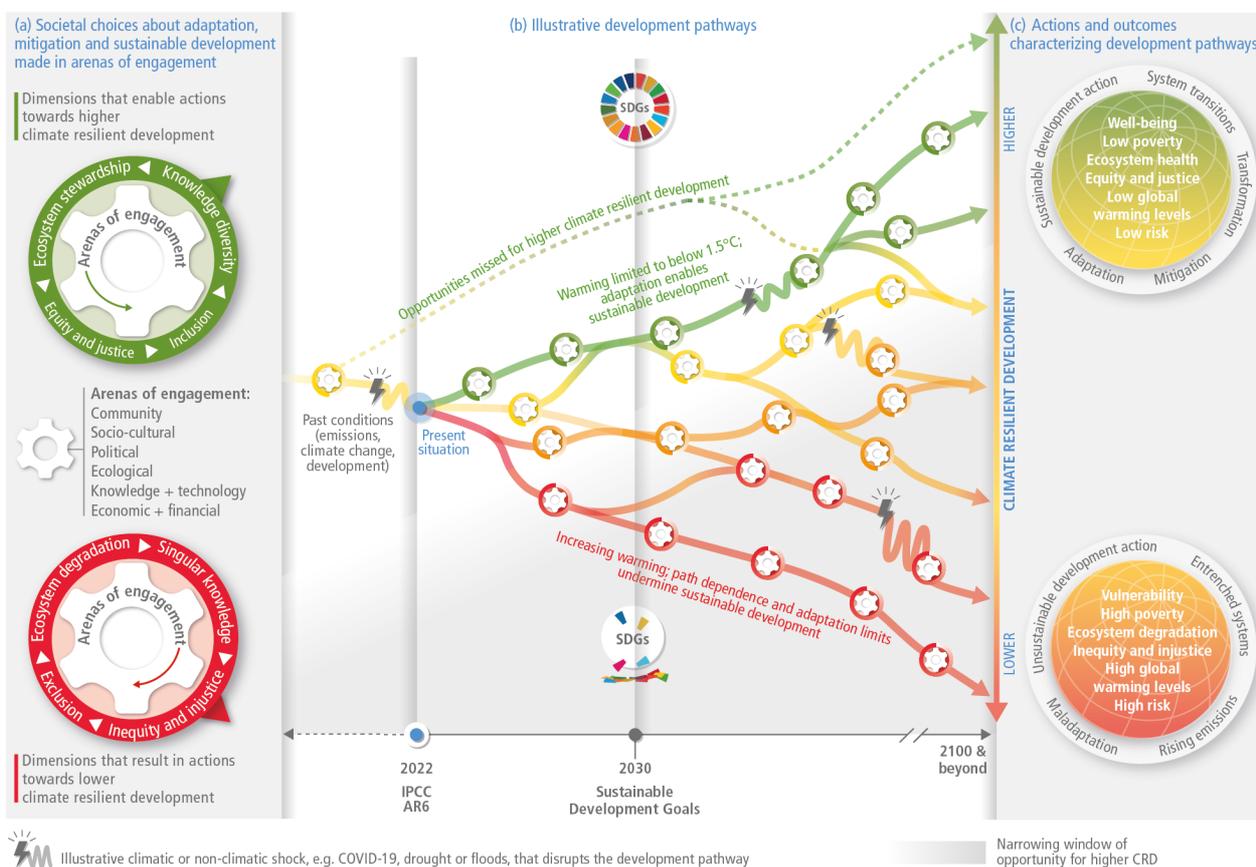


Figure SPM.5: Climate resilient development (CRD) is the process of implementing greenhouse gas mitigation and adaptation measures to support sustainable development. This figure builds on Figure SPM.9 in AR5 WGII (depicting climate resilient pathways) by describing how CRD pathways are the result of cumulative societal choices and actions within multiple arenas. Panel (a): Societal choices towards higher CRD (green cog) or lower CRD (red cog) result from interacting decisions and actions by diverse government, private sector and civil society actors, in the context of climate risks, adaptation limits and development gaps. These actors engage with adaptation, mitigation and development actions in political, economic and financial, ecological, socio-cultural, knowledge and technology, and community arenas from local to international levels. Opportunities for climate resilient development are not equitably distributed around the world. Panel (b): Cumulatively, societal choices, which are made continuously, shift global development pathways towards higher (green) or lower (red) climate resilient development. Past conditions (past emissions, climate change and

development) have already eliminated some development pathways towards higher CRD (dashed green line). Panel (c): Higher CRD is characterised by outcomes that advance sustainable development for all. Climate resilient development is progressively harder to achieve with global warming levels beyond 1.5°C. Inadequate progress towards the Sustainable Development Goals (SDGs) by 2030 reduces climate resilient development prospects. There is a narrowing window of opportunity to shift pathways towards more climate resilient development futures as reflected by the adaptation limits and increasing climate risks, considering the remaining carbon budgets. (Figure SPM.2, Figure SPM.3) {2.6, 3.6, 7.2, 7.3, 7.4, 8.3, 8.4, 8.5, 16.4, 16.5, 17.3, 17.4, 17.5, 18.1, 18.2, 18.3, 18.4, Figure 18.1, Figure 18.2, Figure 18.3, Box 18.1, CCB COVID, CCB GENDER, CCB HEALTH, CCB INDIG, CCB SLR, AR6 WGI Table SPM.1 and Table SPM.2, SR1.5 Figure SPM.1, Figure TS.14b}

Enabling Climate Resilient Development

SPM.D.2 Climate resilient development is enabled when governments, civil society and the private sector make inclusive development choices that prioritise risk reduction, equity and justice, and when decision-making processes, finance and actions are integrated across governance levels, sectors and timeframes (*very high confidence*). Climate resilient development is facilitated by international cooperation and by governments at all levels working with communities, civil society, educational bodies, scientific and other institutions, media, investors and businesses; and by developing partnerships with traditionally marginalised groups, including women, youth, Indigenous Peoples, local communities and ethnic minorities (*high confidence*). These partnerships are most effective when supported by enabling political leadership, institutions, resources, including finance, as well as climate services, information and decision support tools (*high confidence*). (Figure SPM.5) {1.3, 1.4, 1.5, 2.7, 3.6, 4.8, 5.14, 6.4, 7.4, 8.5, 8.6, 9.4, 10.6, 11.8, 12.5, 13.11, 14.7, 15.6, 15.7, 17.4, 17.6, 18.4, 18.5, CCP2.4, CCP3.4, CCP4.4, CCP5.4, CCP6.4, CCP7.6, CCB HEALTH, CCB GENDER, CCB INDIG, CCB DEEP, CCB NATURAL, CCB SLR}

SPM.D.2.1 Climate resilient development is advanced when actors work in equitable, just and enabling ways to reconcile divergent interests, values and worldviews, toward equitable and just outcomes (*high confidence*). These practices build on diverse knowledges about climate risk and chosen development pathways account for local, regional and global climate impacts, risks, barriers and opportunities (*high confidence*). Structural vulnerabilities to climate change can be reduced through carefully designed and implemented legal, policy, and process interventions from the local to global that address inequities based on gender, ethnicity, disability, age, location and income (*very high confidence*). This includes rights-based approaches that focus on capacity-building, meaningful participation of the most vulnerable groups, and their access to key resources, including financing, to reduce risk and adapt (*high confidence*). Evidence shows that climate resilient development processes link scientific, Indigenous, local, practitioner and other forms of knowledge, and are more effective and sustainable because they are locally appropriate and lead to more legitimate, relevant and effective actions (*high confidence*). Pathways towards climate resilient development overcome jurisdictional and organizational barriers, and are founded on societal choices that accelerate and deepen key system transitions (*very high confidence*). Planning processes and decision analysis tools can help identify ‘low regrets’ options⁴⁷ that enable mitigation and adaptation in the face of change, complexity, deep uncertainty and divergent views (*medium confidence*). {1.3, 1.4, 1.5, 2.7, 3.6, 4.8, 5.14, 6.4, 7.4, 8.5, 8.6, 9.4, 10.6, 11.8, 12.5, 13.11, 14.7, 15.6, 15.7, 17.2-17.6, 18.2-18.4, CCP2.3-2.4, CCP3.4, CCP4.4, CCP5.4, CCP6.4, CCP7.6, Box 8.7, Box 9.2, CCB HEALTH, CCB INDIG, CCB DEEP, CCB NATURAL, CCB SLR}

SPM.D.2.2 Inclusive governance contributes to more effective and enduring adaptation outcomes and enables climate resilient development (*high confidence*). Inclusive processes strengthen the ability of governments and other stakeholders to jointly consider factors such as the rate and magnitude of change and uncertainties, associated impacts, and timescales of different climate resilient development pathways given past development choices leading to past emissions and scenarios of future global warming (*high confidence*). Associated societal choices are made continuously through interactions in arenas of engagement from local to international levels. The quality and outcome of these interactions helps determine whether development pathways shift towards or away from climate resilient development (*medium confidence*). (Figure SPM.5) {2.7, 3.6, 4.8, 5.14,

6.4, 7.4, 8.5, 8.6, 9.4, 10.6, 11.8, 12.5, 13.11, 14.7, 15.6, 15.7, 17.2-17.6, 18.2, 18.4, CCP2.3-2.4, CCP3.4, CCP4.4, CCP5.4, CCP6.4, CCP7.6, CCB HEALTH, CCB GENDER, CCB INDIG}

SPM.D.2.3 Governance for climate resilient development is most effective when supported by formal and informal institutions and practices that are well-aligned across scales, sectors, policy domains and timeframes. Governance efforts that advance climate resilient development account for the dynamic, uncertain and context-specific nature of climate-related risk, and its interconnections with non-climate risks. Institutions⁴⁸ that enable climate resilient development are flexible and responsive to emergent risks and facilitate sustained and timely action. Governance for climate resilient development is enabled by adequate and appropriate human and technological resources, information, capacities and finance. (*high confidence*) {2.7, 3.6, 4.8, 5.14, 6.3, 6.4, 7.4, 8.5, 8.6, 9.4, 10.6, 11.8, 12.5, 13.11, 14.7, 15.6, 15.7, 17.2-17.6, 18.2, 18.4, CCP2.3-2.4, CCP3.4, CCP4.4, CCP5.4, CCP6.4, CCP7.6, CCB HEALTH, CCB GENDER, CCB INDIG, CCB DEEP, CCB NATURAL, CCB SLR}

Climate Resilient Development for Natural and Human Systems

SPM.D.3 Interactions between changing urban form, exposure and vulnerability can create climate change-induced risks and losses for cities and settlements. However, the global trend of urbanisation also offers a critical opportunity in the near-term, to advance climate resilient development (*high confidence*). Integrated, inclusive planning and investment in everyday decision-making about urban infrastructure, including social, ecological and grey/physical infrastructures, can significantly increase the adaptive capacity of urban and rural settlements. Equitable outcomes contributes to multiple benefits for health and well-being and ecosystem services, including for Indigenous Peoples, marginalised and vulnerable communities (*high confidence*). Climate resilient development in urban areas also supports adaptive capacity in more rural places through maintaining peri-urban supply chains of goods and services and financial flows (*medium confidence*). Coastal cities and settlements play an especially important role in advancing climate resilient development (*high confidence*). {6.2, 6.3, 18.3, Table 6.6, Box 9.8, CCP6.2, CCP2.1, CCP2.2, CWGB URBAN}

SPM.D.3.1 Taking integrated action for climate resilience to avoid climate risk requires urgent decision making for the new built environment and retrofitting existing urban design, infrastructure and land use. Based on socioeconomic circumstances, adaptation and sustainable development actions will provide multiple benefits including for health and well-being, particularly when supported by national governments, non-governmental organisations and international agencies that work across sectors in partnerships with local communities. Equitable partnerships between local and municipal governments, the private sector, Indigenous Peoples, local communities, and civil society can, including through international cooperation, advance climate resilient development by addressing structural inequalities, insufficient financial resources, cross-city risks and the integration of Indigenous knowledge and Local knowledge. (*high confidence*) {6.2, 6.3, 6.4, 7.4, 8.5, 9.4, 10.5, 12.5, 17.4, 18.2, Table 6.6, Table 17.8, Box 18.1, CCP2.4, CCB GENDER, CCB INDIG, CCB FINANCE, CWGB URBAN}

SPM.D.3.2 Rapid global urbanisation offers opportunities for climate resilient development in diverse contexts from rural and informal settlements to large metropolitan areas (*high confidence*). Dominant models of energy intensive and market-led urbanisation, insufficient and misaligned finance and a predominant focus on grey infrastructure in the absence of integration with ecological and social approaches, risks missing opportunities for adaptation and locking in maladaptation (*high confidence*). Poor land use planning and siloed approaches to health, ecological and social planning also exacerbates, vulnerability in already marginalised

⁴⁸ Institutions: Rules, norms and conventions that guide, constrain or enable human behaviours and practices. Institutions can be formally established, for instance through laws and regulations, or informally established, for instance by traditions or customs. Institutions may spur, hinder, strengthen, weaken or distort the emergence, adoption and implementation of climate action and climate governance.

communities (*medium confidence*). Urban climate resilient development is observed to be more effective if it is responsive to regional and local land use development and adaptation gaps, and addresses the underlying drivers of vulnerability (*high confidence*). The greatest gains in well-being can be achieved by prioritizing finance to reduce climate risk for low-income and marginalized residents including people living in informal settlements (*high confidence*). {5.14, 6.1, 6.2, 6.3, 6.4, 6.5, 7.4, 8.5, 8.6, 9.8, 9.9, 10.4, 18.2, Table 17.8, Table 6.6, Figure 6.5, CCB HEALTH, CCP2.2, CCP5.4, CWGB URBAN}

SPM.D.3.3 Urban systems are critical, interconnected sites for enabling climate resilient development, especially at the coast. Coastal cities and settlements play a key role in moving toward higher climate resilient development given firstly, almost 11% of the global population – 896 million people – lived within the Low Elevation Coastal Zone⁴⁹ in 2020, potentially increasing to beyond 1 billion people by 2050, and these people, and associated development and coastal ecosystems, face escalating climate compounded risks, including sea level rise. Secondly, these coastal cities and settlements make key contributions to climate resilient development through their vital role in national economies and inland communities, global trade supply chains, cultural exchange, and centres of innovation. (*high confidence*) {6.2, Box 15.2, CCP2.1, CCP2.2, Table CCP2.4, CCB SLR}

SPM.D.4 Safeguarding biodiversity and ecosystems is fundamental to climate resilient development, in light of the threats climate change poses to them and their roles in adaptation and mitigation (*very high confidence*). Recent analyses, drawing on a range of lines of evidence, suggest that maintaining the resilience of biodiversity and ecosystem services at a global scale depends on effective and equitable conservation of approximately 30% to 50% of Earth's land, freshwater and ocean areas, including currently near-natural ecosystems (*high confidence*). {2.4, 2.5, 2.6, 3.4, Box 3.4, 3.5, 3.6, 12.5, 13.3, 13.4, 13.5, 13.10, CCB NATURAL, CCB INDIG}

SPM.D.4.1 Building the resilience of biodiversity and supporting ecosystem integrity⁵⁰ can maintain benefits for people, including livelihoods, human health and well-being and the provision of food, fibre and water, as well as contributing to disaster risk reduction and climate change adaptation and mitigation. {2.2, 2.5, 2.6, Table 2.6, Table 2.7, 3.5, 3.6, 5.8, 5.13, 5.14, 12.5, Box 5.11 CCP5.4, CCB NATURAL, CCB ILLNESS, CCB COVID, CCB GENDER, CCB INDIG, CCB MIGRATE}

SPM.D.4.2 Protecting and restoring ecosystems is essential for maintaining and enhancing the resilience of the biosphere (*very high confidence*). Degradation and loss of ecosystems is also a cause of greenhouse gas emissions and is at increasing risk of being exacerbated by climate change impacts, including droughts and wildfire (*high confidence*). Climate resilient development avoids adaptation and mitigation measures that damage ecosystems (*high confidence*). Documented examples of adverse impacts of land-based measures intended as mitigation, when poorly implemented, include afforestation of grasslands, savannas and peatlands, and risks from bioenergy crops at large scale to water supply, food security and biodiversity (*high confidence*). {2.4, 2.5, Box 2.2, 3.4, 3.5, Box 3.4, Box 9.3, CCP7.3, CCB NATURAL, CWGB BIOECONOMY}

SPM.D.4.3 Biodiversity and ecosystem services have limited capacity to adapt to increasing global warming levels, which will make climate resilient development progressively harder to achieve beyond 1.5°C warming (*very high confidence*). Consequences of current and future global warming for climate resilient development include reduced effectiveness of EbA and approaches to climate change mitigation based on ecosystems and amplifying feedbacks to the climate system (*high confidence*). {2.4, 2.5, 2.6, 3.4, 3.5, 3.6, 12.5, 13.2, 13.3, 13.10, 14.5, 14.5, 15.3, 17.3, 17.6, Box 14.3, Box 3.4, Table 5.2, CCP5.3, CCP5.4, Figure TS.14d, CCB EXTREMES, CCB ILLNESS, CCB NATURAL, CCB SLR, SR1.5, SRCCL, SROCC}

⁴⁹ LECZ, coastal areas below 10 m of elevation above sea level that are hydrologically connected to the sea

⁵⁰ Ecosystem integrity refers to the ability of ecosystems to maintain key ecological processes, recover from disturbance, and adapt to new conditions.

Achieving Climate Resilient Development

SPM.D.5 It is unequivocal that climate change has already disrupted human and natural systems. Past and current development trends (past emissions, development and climate change) have not advanced global climate resilient development (*very high confidence*). Societal choices and actions implemented in the next decade determine the extent to which medium- and long-term pathways will deliver higher or lower climate resilient development (*high confidence*). Importantly climate resilient development prospects are increasingly limited if current greenhouse gas emissions do not rapidly decline, especially if 1.5°C global warming is exceeded in the near term (*high confidence*). These prospects are constrained by past development, emissions and climate change, and enabled by inclusive governance, adequate and appropriate human and technological resources, information, capacities and finance (*high confidence*). {1.2, 1.4, 1.5, 2.6, 2.7, 3.6, 4.7, 4.8, 5.14, 6.4, 7.4, 8.3, 8.5, 8.6, 9.3, 9.4, 9.5, 10.6, 11.8, 12.5, 13.10, 13.11, 14.7, 15.3, 15.6, 15.7, 16.2, 16.4, 16.5, 16.6, 17.2-17.6, 18.2-18.5, CCP2.3-2.4, CCP3.4, CCP4.4, Table CCP5.2, CCP5.3, CCP5.4, CCP6.3, CCP6.4, CCP7.5, CCP7.6, Figure TS.14d, CCB DEEP, CCB HEALTH, CCB INDIG, CCB DEEP, CCB NATURAL, CCB SLR}

SPM.D.5.1 Climate resilient development is already challenging at current global warming levels (*high confidence*). The prospects for climate resilient development will be further limited if global warming levels exceeds 1.5°C (*high confidence*) and not be possible in some regions and sub-regions if the global warming level exceeds 2°C (*medium confidence*). Climate resilient development is most constrained in regions/subregions in which climate impacts and risks are already advanced, including low-lying coastal cities and settlements, small islands, deserts, mountains and polar regions (*high confidence*). Regions and subregions with high levels of poverty, water, food and energy insecurity, vulnerable urban environments, degraded ecosystems and rural environments, and/or few enabling conditions, face many non-climate challenges that inhibit climate resilient development which are further exacerbated by climate change (*high confidence*). {1.2, 9.3, 9.4, 9.5, 10.6, 11.8, 12.5, 13.10, 14.7, 15.3, CCP2.3, CCP3.4, CCP4.4, Box 6.6, CCP5.3, Table CCP5.2, CCP6.3, CCP7.5, Figure TS.14d}

SPM.D.5.2 Inclusive governance, investment aligned with climate resilient development, access to appropriate technology and rapidly scaled-up finance, and capacity building of governments at all levels, the private sector and civil society enable climate resilient development. Experience shows that climate resilient development processes are timely, anticipatory, integrative, flexible and action focused. Common goals and social learning build adaptive capacity for climate resilient development. When implementing adaptation and mitigation together, and taking trade-offs into account, multiple benefits and synergies for human well-being as well as ecosystem and planetary health can be realised. Prospects for climate resilient development are increased by inclusive processes involving local knowledge and Indigenous Knowledge as well as processes that coordinate across risks and institutions. Climate resilient development is enabled by increased international cooperation including mobilising and enhancing access to finance, particularly for vulnerable regions, sectors and groups. (*high confidence*) (Figure SPM.5) {2.7, 3.6, 4.8, 5.14, 6.4, 7.4, 8.5, 8.6, 9.4, 10.6, 11.8, 12.5, 13.11, 14.7, 15.6, 15.7, 17.2-17.6, 18.2-18.5, CCP2.3-2.4, CCP3.4, CCP4.4, CCP5.4, CCP6.4, CCP7.6, CCB HEALTH, CCB INDIG, CCB DEEP, CCB NATURAL, CCB SLR}

SPM.D.5.3 The cumulative scientific evidence is unequivocal: Climate change is a threat to human well-being and planetary health. Any further delay in concerted anticipatory global action on adaptation and mitigation will miss a brief and rapidly closing window of opportunity to secure a liveable and sustainable future for all. (*very high confidence*) {1.2, 1.4, 1.5, 16.2, 16.4, 16.5, 16.6, 17.4, 17.5, 17.6, 18.3, 18.4, 18.5, CWGB URBAN, CCB DEEP, Table SM16.24, WGI SPM, SROCC SPM, SRCCL SPM}

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INTERGOVERNMENTAL PANEL ON climate change

Climate Change 2022

Mitigation of Climate Change

Summary for Policymakers



Working Group III contribution to the
Sixth Assessment Report of the
Intergovernmental Panel on Climate Change



**WORKING GROUP III CONTRIBUTION
TO THE IPCC SIXTH ASSESSMENT REPORT (AR6)**

Summary for Policymakers

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A. Introduction and framing

The Working Group III (WG III) contribution to the IPCC's Sixth Assessment Report (AR6) assesses literature on the scientific, technological, environmental, economic and social aspects of mitigation of climate change. [FOOTNOTE 1] Levels of confidence [FOOTNOTE 2] are given in () brackets. Numerical ranges are presented in square [] brackets. References to Chapters, Sections, Figures and Boxes in the underlying report and Technical Summary (TS) are given in {} brackets.

FOOTNOTE 1: The Report covers literature accepted for publication by 11 October 2021.

FOOTNOTE 2: Each finding is grounded in an evaluation of underlying evidence and agreement. A level of confidence is expressed using five qualifiers, typeset in italics: *very low*, *low*, *medium*, *high* and *very high*. The assessed likelihood of an outcome or a result is described as: virtually certain 99–100% probability, very likely 90–100%, likely 66–100%, more likely than not 50–100%, about as likely as not 33–66%, unlikely 0–33%, very unlikely 0–10%, exceptionally unlikely 0–1%. Additional terms may also be used when appropriate, consistent with the IPCC uncertainty guidance: <https://www.ipcc.ch/site/assets/uploads/2018/05/uncertainty-guidance-note.pdf>.

The report reflects new findings in the relevant literature and builds on previous IPCC reports, including the WG III contribution to the IPCC's Fifth Assessment Report (AR5), the WG I and WG II contributions to AR6 and the three Special Reports in the Sixth Assessment cycle, [FOOTNOTE 3] as well as other UN assessments. Some of the main developments relevant for this report include {TS.1, TS.2}:

FOOTNOTE 3: The three Special Reports are: Global Warming of 1.5°C: an IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty (2018); Climate Change and Land: an IPCC Special Report on climate change, desertification, land degradation, sustainable land management, food security, and greenhouse gas fluxes in terrestrial ecosystems (2019); IPCC Special Report on the Ocean and Cryosphere in a Changing Climate (2019).

- **An evolving international landscape.** The literature reflects, among other factors: developments in the UN Framework Convention on Climate Change (UNFCCC) process, including the outcomes of the Kyoto Protocol and the adoption of the Paris Agreement {13, 14, 15, 16}; the UN 2030 Agenda for Sustainable Development including the Sustainable Development Goals (SDGs) {1, 3, 4, 17}; and the evolving roles of international cooperation {14}, finance {15} and innovation {16}.
- **Increasing diversity of actors and approaches to mitigation.** Recent literature highlights the growing role of non-state and sub-national actors including cities, businesses, Indigenous Peoples, citizens including local communities and youth, transnational initiatives, and public-private entities in the global effort to address climate change {5, 13, 14, 15, 16, 17}. Literature documents the global spread of climate policies and cost declines of existing and emerging low emission technologies, along with varied types and levels of mitigation efforts, and sustained reductions in greenhouse gas (GHG) emissions in some countries {2, 5, 6, 8, 12, 13, 16}, and the impacts of, and some lessons from, the COVID-19 pandemic. {1, 2, 3, 5, 13, 15, Box TS.1, Cross-Chapter Box 1 in Chapter 1}

- **Close linkages between climate change mitigation, adaptation and development pathways.** The development pathways taken by countries at all stages of economic development impact GHG emissions and hence shape mitigation challenges and opportunities, which vary across countries and regions. Literature explores how development choices and the establishment of enabling conditions for action and support influence the feasibility and the cost of limiting emissions {1, 3, 4, 5, 13, 15, 16}. Literature highlights that climate change mitigation action designed and conducted in the context of sustainable development, equity, and poverty eradication, and rooted in the development aspirations of the societies within which they take place, will be more acceptable, durable and effective {1, 3, 4, 5}. This report covers mitigation from both targeted measures, and from policies and governance with other primary objectives.
- **New approaches in the assessment.** In addition to the sectoral and systems chapters {3, 6, 7, 8, 9, 10, 11, 12}, the report includes, for the first time in a WG III report, chapters dedicated to demand for services, and social aspects of mitigation {5, Box TS.11}, and to innovation, technology development and transfer {16}. The assessment of future pathways in this report covers near term (to 2030), medium term (up to 2050), and long term (to 2100) timescales, combining assessment of existing pledges and actions {4, 5}, with an assessment of emissions reductions, and their implications, associated with long-term temperature outcomes up to the year 2100 {3}. [FOOTNOTE 4] The assessment of modelled global pathways addresses ways of shifting development pathways towards sustainability. Strengthened collaboration between IPCC Working Groups is reflected in Cross-Working Group boxes that integrate physical science, climate risks and adaptation, and the mitigation of climate change. [FOOTNOTE 5]

FOOTNOTE 4: The term ‘temperature’ is used in reference to “global surface temperatures” throughout this SPM as defined in footnote 8 of WG I SPM. See FOOTNOTE 14 of Table SPM.1. Emission pathways and associated temperature changes are calculated using various forms of models, as summarised in Box SPM.1 and Chapter 3 and discussed in Annex III.

FOOTNOTE 5: Namely: Economic Benefits from Avoided Climate Impacts along Long-Term Mitigation Pathways {Cross-Working Group Box 1 in Chapter 3}; Urban: Cities and Climate Change {Cross-Working Group Box 2 in Chapter 8}; and Mitigation and Adaptation via the Bioeconomy {Cross-Working Group Box 3 in Chapter 12}.

- **Increasing diversity of analytic frameworks from multiple disciplines including social sciences.** This report identifies multiple analytic frameworks to assess the drivers of, barriers to and options for, mitigation action. These include: economic efficiency including the benefits of avoided impacts; ethics and equity; interlinked technological and social transition processes; and socio-political frameworks, including institutions and governance {1, 3, 13, Cross-Chapter Box 12 in Chapter 16}. These help to identify risks and opportunities for action including co-benefits and just and equitable transitions at local, national and global scales. {1, 3, 4, 5, 13, 14, 16, 17}

Section B of this Summary for Policymakers (SPM) assesses *Recent developments and current trends*, including data uncertainties and gaps. Section C, *System transformations to limit global warming*, identifies emission pathways and alternative mitigation portfolios consistent with limiting global warming to different levels, and assesses specific mitigation options at the sectoral and system level. Section D addresses *Linkages between mitigation, adaptation, and sustainable development*. Section E, *Strengthening the response*, assesses knowledge of how enabling conditions of institutional design, policy, finance, innovation and governance arrangements can contribute to climate change mitigation in the context of sustainable development.

B. Recent developments and current trends

B.1 Total net anthropogenic GHG emissions [FOOTNOTE 6] have continued to rise during the period 2010–2019, as have cumulative net CO₂ emissions since 1850. Average annual GHG emissions during 2010–2019 were higher than in any previous decade, but the rate of growth between 2010 and 2019 was lower than that between 2000 and 2009. (*high confidence*) (Figure SPM.1) {Figure 2.2, Figure 2.5, Table 2.1, 2.2, Figure TS.2}

FOOTNOTE 6: Net GHG emissions in this report refer to releases of greenhouse gases from anthropogenic sources minus removals by anthropogenic sinks, for those species of gases that are reported under the common reporting format of the United Nations Framework Convention on Climate Change (UNFCCC): CO₂ from fossil fuel combustion and industrial processes (CO₂-FFI); net CO₂ emissions from land use, land use change and forestry (CO₂-LULUCF); methane (CH₄); nitrous oxide (N₂O); and fluorinated gases (F-gases) comprising hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulphur hexafluoride (SF₆) as well as nitrogen trifluoride (NF₃). Different datasets for GHG emissions exist, with varying time horizons and coverage of sectors and gases, including some that go back to 1850. In this report, GHG emissions are assessed from 1990, and CO₂ sometimes also from 1850. Reasons for this include data availability and robustness, scope of the assessed literature, and the differing warming impacts of non-CO₂ gases over time.

B.1.1 Global net anthropogenic GHG emissions were 59±6.6 GtCO₂-eq [FOOTNOTE 7, 8] in 2019, about 12% (6.5 GtCO₂-eq) higher than in 2010 and 54% (21 GtCO₂-eq) higher than in 1990. The annual average during the decade 2010–2019 was 56±6.0 GtCO₂-eq, 9.1 GtCO₂-eq yr⁻¹ higher than in 2000–2009. This is the highest increase in average decadal emissions on record. The average annual rate of growth slowed from 2.1% yr⁻¹ between 2000 and 2009 to 1.3% yr⁻¹ between 2010 and 2019. (*high confidence*) (Figure SPM.1) {Figure 2.2, Figure 2.5, Table 2.1, 2.2, Figure TS.2}

FOOTNOTE 7: GHG emission metrics are used to express emissions of different greenhouse gases in a common unit. Aggregated GHG emissions in this report are stated in CO₂-equivalent (CO₂-eq) using the Global Warming Potential with a time horizon of 100 years (GWP100) with values based on the contribution of Working Group I to the AR6. The choice of metric depends on the purpose of the analysis and all GHG emission metrics have limitations and uncertainties, given that they simplify the complexity of the physical climate system and its response to past and future GHG emissions. {Chapter 2 SM 2.3, Cross-Chapter Box 2 in Chapter 2, Box TS.2, WG I Chapter 7 Supplementary Material}

FOOTNOTE 8: In this SPM, uncertainty in historic GHG emissions is reported using 90 % uncertainty intervals unless stated otherwise. GHG emission levels are rounded to two significant digits; as a consequence, small differences in sums due to rounding may occur.

B.1.2 Growth in anthropogenic emissions has persisted across all major groups of GHGs since 1990, albeit at different rates. By 2019, the largest growth in absolute emissions occurred in CO₂ from fossil fuels and industry followed by CH₄, whereas the highest relative growth occurred in fluorinated gases, starting from low levels in 1990 (*high confidence*). Net anthropogenic CO₂ emissions from land use, land-use change and forestry (CO₂-LULUCF) are subject to large uncertainties and high annual variability, with *low confidence* even in the direction of the long-term trend [FOOTNOTE 9]. (Figure SPM.1) {Figure 2.2, Figure 2.5, 2.2, Figure TS.2}

FOOTNOTE 9: Global databases make different choices about which emissions and removals occurring on land are considered anthropogenic. Currently, net CO₂ fluxes from land reported by global book-keeping models used here are estimated to be about ~5.5 GtCO₂ yr⁻¹ higher than the aggregate

global net emissions based on national GHG inventories. This difference, which has been considered in the literature, mainly reflects differences in how anthropogenic forest sinks and areas of managed land are defined. Other reasons for this difference, which are more difficult to quantify, can arise from the limited representation of land management in global models and varying levels of accuracy and completeness of estimated LULUCF fluxes in national GHG inventories. Neither method is inherently preferable. Even when the same methodological approach is applied, the large uncertainty of CO₂-LULUCF emissions can lead to substantial revisions to estimated emissions. {Cross-Chapter Box 3 in Chapter 3, 7.2, SRCCL SPM A.3.3}

B.1.3 Historical cumulative net CO₂ emissions from 1850 to 2019 were 2400±240 GtCO₂ (*high confidence*). Of these, more than half (58%) occurred between 1850 and 1989 [1400±195 GtCO₂], and about 42% between 1990 and 2019 [1000±90 GtCO₂]. About 17% of historical cumulative net CO₂ emissions since 1850 occurred between 2010 and 2019 [410±30 GtCO₂]. [FOOTNOTE 10] By comparison, the current central estimate of the remaining carbon budget from 2020 onwards for limiting warming to 1.5°C with a probability of 50% has been assessed as 500 Gt CO₂, and as 1150 Gt CO₂ for a probability of 67% for limiting warming to 2°C. Remaining carbon budgets depend on the amount of non-CO₂ mitigation (±220 Gt CO₂) and are further subject to geophysical uncertainties. Based on central estimates only, cumulative net CO₂ emissions between 2010-2019 compare to about four fifths of the size of the remaining carbon budget from 2020 onwards for a 50% probability of limiting global warming to 1.5°C, and about one third of the remaining carbon budget for a 67% probability to limit global warming to 2°C. Even when taking uncertainties into account, historical emissions between 1850 and 2019 constitute a large share of total carbon budgets for these global warming levels [FOOTNOTE 11, 12]. Based on central estimates only, historical cumulative net CO₂ emissions between 1850-2019 amount to about four fifths [FOOTNOTE 12] of the total carbon budget for a 50% probability of limiting global warming to 1.5°C (central estimate about 2900 GtCO₂), and to about two thirds [FOOTNOTE 12] of the total carbon budget for a 67% probability to limit global warming to 2°C (central estimate about 3550 GtCO₂). {Figure 2.7, 2.2, Figure TS.3, WG I Table SPM.2}

FOOTNOTE 10: For consistency with WGI, historical cumulative CO₂ emissions from 1850-2019 are reported using 68% confidence intervals.

FOOTNOTE 11: The carbon budget is the maximum amount of cumulative net global anthropogenic CO₂ emissions that would result in limiting global warming to a given level with a given likelihood, taking into account the effect of other anthropogenic climate forcers. This is referred to as the total carbon budget when expressed starting from the pre-industrial period, and as the remaining carbon budget when expressed from a recent specified date. The total carbon budgets reported here are the sum of historical emissions from 1850 to 2019 and the remaining carbon budgets from 2020 onwards, which extend until global net zero CO₂ emissions are reached. {Annex I: Glossary; WG I SPM}

FOOTNOTE 12: Uncertainties for total carbon budgets have not been assessed and could affect the specific calculated fractions.

B.1.4 Emissions of CO₂-FFI dropped temporarily in the first half of 2020 due to responses to the COVID-19 pandemic (*high confidence*), but rebounded by the end of the year (*medium confidence*). The annual average CO₂-FFI emissions reduction in 2020 relative to 2019 was about 5.8% [5.1-6.3%], or 2.2 [1.9-2.4] GtCO₂ (*high confidence*). The full GHG emissions impact of the COVID-19 pandemic could not be assessed due to a lack of data regarding non-CO₂ GHG emissions in 2020. {Cross-Chapter Box 1 in Chapter 1, Figure 2.6, 2.2, Box TS.1, Box TS.1 Figure 1}

Global net anthropogenic emissions have continued to rise across all major groups of greenhouse gases.

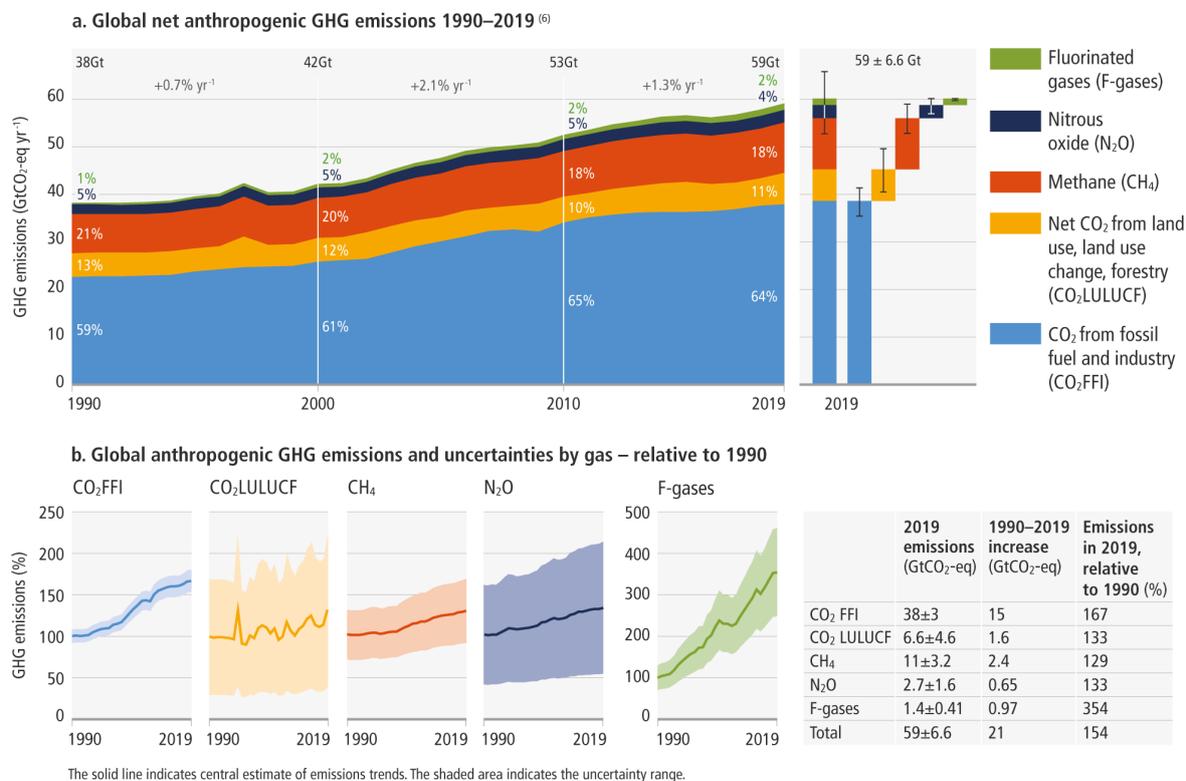


Figure SPM.1: Global net anthropogenic GHG emissions (GtCO₂-eq yr⁻¹) 1990–2019

Global net anthropogenic GHG emissions include CO₂ from fossil fuel combustion and industrial processes (CO₂-FFI); net CO₂ from land use, land use change and forestry (CO₂-LULUCF) [FOOTNOTE 9]; methane (CH₄); nitrous oxide (N₂O); fluorinated gases (HFCs; PFCs, SF₆, NF₃). [FOOTNOTE 6]

Panel a shows aggregate annual global net anthropogenic GHG emissions by groups of gases from 1990 to 2019 reported in GtCO₂-eq converted based on global warming potentials with a 100-year time horizon (GWP100-AR6) from the IPCC Sixth Assessment Report Working Group I (Chapter 7). The fraction of global emissions for each gas is shown 1990, 2000, 2010, 2019; as well as the aggregate average annual growth rate between these decades. At the right side of Panel a, GHG emissions in 2019 are broken down into individual components with the associated uncertainties [90% confidence interval] indicated by the error bars: CO₂ FFI ±8%, CO₂-LULUCF ±70%, CH₄ ±30%, N₂O ±60%, F-gases ±30%, GHG ±11%. Uncertainties in GHG emissions are assessed in the Supplementary Material to Chapter 2. The single year peak of emissions in 1997 was due to higher CO₂-LULUCF emissions from a forest and peat fire event in South East Asia.

Panel b shows global anthropogenic CO₂-FFI, net CO₂-LULUCF, CH₄, N₂O and fluorinated gas emissions individually for the period 1990–2019, normalised relative to 100 in 1990. Note the different scale for the included fluorinated gas emissions compared to other gases, highlighting its rapid growth from a low base. Shaded areas indicate the uncertainty range. Uncertainty ranges as shown here are specific for individual groups of greenhouse gases and cannot be compared. The table shows the central estimate for: absolute emissions in 2019, the absolute change in emissions between 1990 and 2019, and emissions in 2019 expressed as a percentage of 1990 emissions. {2.2, Figure 2.5, Figure TS.2, Chapter 2 SM}

FOOTNOTE 9: Global databases make different choices about which emissions and removals occurring on land are considered anthropogenic. Currently, net CO₂ fluxes from land reported by global book-keeping models used here are estimated to be about ~5.5 GtCO₂ yr⁻¹ higher than the aggregate global net emissions based on national GHG inventories. This difference, which has been considered in the literature, mainly reflects differences in how anthropogenic forest sinks and areas of managed land are defined. Other reasons for this difference, which are more difficult to quantify, can arise from the limited representation of land management in global models and varying levels of accuracy and completeness of estimated LULUCF fluxes in national GHG inventories. Neither method is inherently preferable. Even when the same methodological approach is applied, the large uncertainty of CO₂-LULUCF emissions can lead to substantial revisions to estimated emissions. {Cross-Chapter Box 3 in Chapter 3, 7.2, SRCCL SPM A.3.3}

FOOTNOTE 6: Net GHG emissions in this report refer to releases of greenhouse gases from anthropogenic sources minus removals by anthropogenic sinks, for those species of gases that are reported under the common reporting format of the United Nations Framework Convention on Climate Change (UNFCCC): CO₂ from fossil fuel combustion and industrial processes (CO₂-FFI); net CO₂ emissions from land use, land use change and forestry (CO₂-LULUCF); methane (CH₄); nitrous oxide (N₂O); and fluorinated gases (F-gases) comprising hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulphur hexafluoride (SF₆) as well as nitrogen trifluoride (NF₃). Different datasets for GHG emissions exist, with varying time horizons and coverage of sectors and gases, including some that go back to 1850. In this report, GHG emissions are assessed from 1990, and CO₂ sometimes also from 1850. Reasons for this include data availability and robustness, scope of the assessed literature, and the differing warming impacts of non-CO₂ gases over time.

B.2 Net anthropogenic GHG emissions have increased since 2010 across all major sectors globally. An increasing share of emissions can be attributed to urban areas. Emissions reductions in CO₂ from fossil fuels and industrial processes, due to improvements in energy intensity of GDP and carbon intensity of energy, have been less than emissions increases from rising global activity levels in industry, energy supply, transport, agriculture and buildings. (*high confidence*) {2.2, 2.4, 6.3, 7.2, 8.3, 9.3, 10.1, 11.2}

B.2.1 In 2019, approximately 34% [20 GtCO₂-eq] of total net anthropogenic GHG emissions came from the energy supply sector, 24% [14 GtCO₂-eq] from industry, 22% [13 GtCO₂-eq] from agriculture, forestry and other land use (AFOLU), 15% [8.7 GtCO₂-eq] from transport and 6% [3.3 GtCO₂-eq] from buildings.¹³ If emissions from electricity and heat production are attributed to the sectors that use the final energy, 90% of these indirect emissions are allocated to the industry and buildings sectors, increasing their relative GHG emissions shares from 24% to 34%, and from 6% to 16%, respectively. After reallocating emissions from electricity and heat production, the energy supply sector accounts for 12% of global net anthropogenic GHG emissions. (*high confidence*) {Figure 2.12, 2.2, 6.3, 7.2, 9.3, 10.1, 11.2, Figure TS.6}

FOOTNOTE 13: Sector definitions can be found in Annex II 9.1.

B.2.2 Average annual GHG emissions growth between 2010 and 2019 slowed compared to the previous decade in energy supply [from 2.3% to 1.0%] and industry [from 3.4% to 1.4%], but remained roughly constant at about 2% per year in the transport sector (*high confidence*). Emissions growth in AFOLU, comprising emissions from agriculture (mainly CH₄ and N₂O) and forestry and other land use (mainly CO₂) is more uncertain than in other sectors due to the high share and uncertainty of CO₂-LULUCF emissions (*medium confidence*). About half of total net AFOLU emissions are from CO₂-LULUCF, predominantly from deforestation. [FOOTNOTE 14] (*medium confidence*). {Figure 2.13, 2.2, 6.3, 7.2, Figure 7.3, 9.3, 10.1, 11.2, TS.3}

FOOTNOTE 14: Land overall constituted a net sink of $-6.6 (\pm 4.6)$ GtCO₂ yr⁻¹ for the period 2010–2019, comprising a gross sink of $-12.5 (\pm 3.2)$ GtCO₂ yr⁻¹ resulting from responses of all land to both anthropogenic environmental change and natural climate variability, and net anthropogenic CO₂-LULUCF emissions $+5.9 (\pm 4.1)$ GtCO₂ yr⁻¹ based on book-keeping models. {2.2, 7.2, Table 7.1}

B.2.3 The global share of emissions that can be attributed to urban areas is increasing. In 2015, urban emissions were estimated to be 25 GtCO₂-eq (about 62% of the global share) and in 2020, 29 GtCO₂-eq (67–72% of the global share).¹⁵ The drivers of urban GHG emission are complex and include population size, income, state of urbanisation and urban form. (*high confidence*) {8.1, 8.3}

FOOTNOTE 15: This estimate is based on consumption-based accounting, including both direct emissions from within urban areas, and indirect emissions from outside urban areas related to the production of electricity, goods and services consumed in cities. These estimates include all CO₂ and CH₄ emission categories except for aviation and marine bunker fuels, land-use change, forestry and agriculture. {8.1, Annex I: Glossary}

B.2.4 Global energy intensity (total primary energy per unit GDP) decreased by 2% yr⁻¹ between 2010 and 2019. Carbon intensity (CO₂ from fossil fuel combustion and industrial processes (CO₂ FFI) per unit primary energy) decreased by 0.3% yr⁻¹, with large regional variations, over the same period mainly due to fuel switching from coal to gas, reduced expansion of coal capacity, and increased use of renewables. This reversed the trend observed for 2000–2009. For comparison, the carbon intensity of primary energy is projected to decrease globally by about 3.5% yr⁻¹ between 2020 and 2050 in modelled scenarios that limit warming to 2°C (>67%), and by about 7.7% yr⁻¹ globally in scenarios that limit warming to 1.5°C (>50%) with no or limited overshoot.¹⁶ (*high confidence*) {Figure 2.16, 2.2, 2.4, Table 3.4, 3.4, 6.3}

FOOTNOTE 16: See Box SPM.1 for the categorisation of modelled long-term emission scenarios based on projected temperature outcomes and associated probabilities adopted in this report.

B.3 Regional contributions [FOOTNOTE 17] to global GHG emissions continue to differ widely. Variations in regional, and national per capita emissions partly reflect different development stages, but they also vary widely at similar income levels. The 10% of households with the highest per capita emissions contribute a disproportionately large share of global household GHG emissions. At least 18 countries have sustained GHG emission reductions for longer than 10 years. (*high confidence*) (Figure SPM.2) {Figure 1.1, Figure 2.9, Figure 2.10, Figure 2.25, 2.2, 2.3, 2.4, 2.5, 2.6, Figure TS.4, Figure TS.5}

FOOTNOTE 17: See Working Group III Annex II, Part 1 for regional groupings adopted in this report.

B.3.1 GHG emissions trends over 1990–2019 vary widely across regions and over time, and across different stages of development as shown in Figure SPM.2. Average global per capita net anthropogenic GHG emissions increased from 7.7 to 7.8 tCO₂-eq, ranging from 2.6 tCO₂-eq to 19 tCO₂-eq across regions. Least Developed Countries (LDCs) and Small Island Developing States (SIDS) have much lower per capita emissions (1.7 tCO₂-eq, 4.6 tCO₂-eq, respectively) than the global average (6.9 tCO₂-eq), excluding CO₂-LULUCF [FOOTNOTE 18]. (*high confidence*) (Figure SPM.2) {Figure 1.2, Figure 2.9, Figure 2.10, 2.2, Figure TS.4}

FOOTNOTE 18: In 2019, LDCs are estimated to have emitted 3.3% of global GHG emissions, and SIDS are estimated to have emitted 0.60% of global GHG emissions, excluding CO₂-LULUCF. These

country groupings cut across geographic regions and are not depicted separately in Fig SPM2. {Figure 2.10}

B.3.2 Historical contributions to cumulative net anthropogenic CO₂ emissions between 1850 and 2019 vary substantially across regions in terms of total magnitude, but also in terms of contributions to CO₂-FFI (1650 +/- 73 GtCO₂-eq) and net CO₂-LULUCF (760 +/- 220 GtCO₂-eq) emissions.[FOOTNOTE 19] Globally, the major share of cumulative CO₂-FFI emissions is concentrated in a few regions, while cumulative CO₂-LULUCF [FOOTNOTE 9] emissions are concentrated in other regions. LDCs contributed less than 0.4% of historical cumulative CO₂-FFI emissions between 1850 and 2019, while SIDS contributed 0.5%. (*high confidence*) (Figure SPM.2) {Figure 2.10, 2.2, TS.3, Figure 2.7}

FOOTNOTE 9: Global databases make different choices about which emissions and removals occurring on land are considered anthropogenic. Currently, net CO₂ fluxes from land reported by global book-keeping models used here are estimated to be about ~5.5 GtCO₂ yr⁻¹ higher than the aggregate global net emissions based on national GHG inventories. This difference, which has been considered in the literature, mainly reflects differences in how anthropogenic forest sinks and areas of managed land are defined. Other reasons for this difference, which are more difficult to quantify, can arise from the limited representation of land management in global models and varying levels of accuracy and completeness of estimated LULUCF fluxes in national GHG inventories. Neither method is inherently preferable. Even when the same methodological approach is applied, the large uncertainty of CO₂-LULUCF emissions can lead to substantial revisions to estimated emissions. {Cross-Chapter Box 3 in Chapter 3, 7.2, SRCL SPM A.3.3}

FOOTNOTE 19: For consistency with WGI, historical cumulative CO₂ emissions from 1850-2019 are reported using 68% confidence intervals.

B.3.3 In 2019, around 48% of the global population lives in countries emitting on average more than 6t CO₂-eq per capita, excluding CO₂-LULUCF. 35% live in countries emitting more than 9 tCO₂-eq per capita. Another 41% live in countries emitting less than 3 tCO₂-eq per capita. A substantial share of the population in these low emitting countries lack access to modern energy services (FOOTNOTE 20). Eradicating extreme poverty, energy poverty, and providing decent living standards (FOOTNOTE 21) to all in these regions in the context of achieving sustainable development objectives, in the near-term, can be achieved without significant global emissions growth. (*high confidence*) (Figure SPM.2) {Figure 1.2, 2.2, 2.4, 2.6, 3.7, 4.2, 6.7, Figure TS.4, Figure TS.5}

FOOTNOTE 20: In this report, access to modern energy services is defined as access to clean, reliable and affordable energy services for cooking and heating, lighting, communications, and productive uses (See Annex I: Glossary)

FOOTNOTE 21: In this report, decent living standards are defined as a set of minimum material requirements essential for achieving basic human well-being, including nutrition, shelter, basic living conditions, clothing, health care, education, and mobility. (See 5.1)

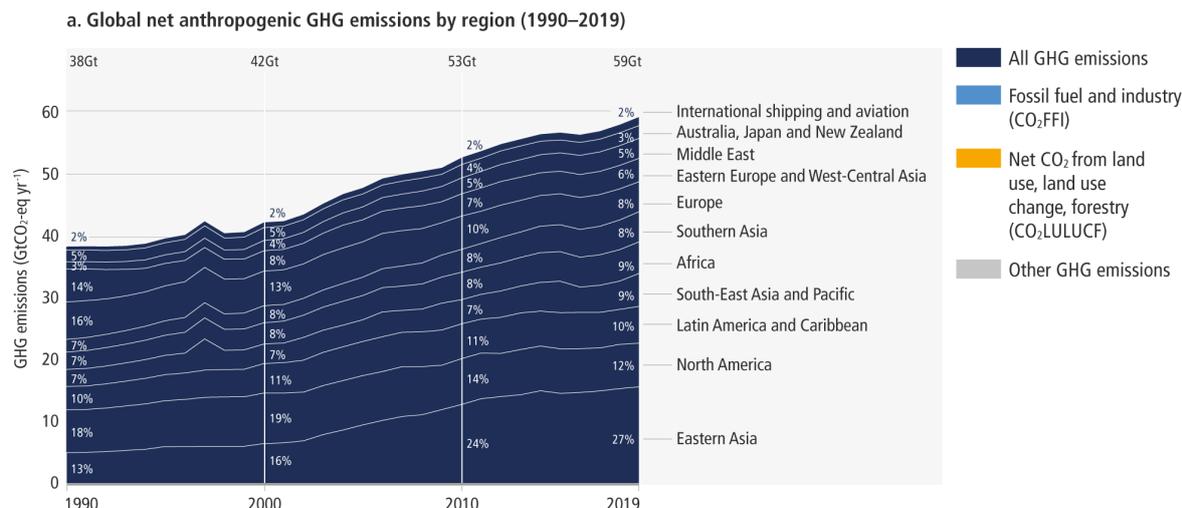
B.3.4 Globally, the 10% of households with the highest per capita emissions contribute 34-45% of global consumption-based household GHG emissions [FOOTNOTE 22], while the middle 40% contribute 40-53%, and the bottom 50% contribute 13-15%. (*high confidence*) {2.6, Figure 2.25}

FOOTNOTE 22: Consumption-based emissions refer to emissions released to the atmosphere to generate the goods and services consumed by a certain entity (e.g., a person, firm, country, or region).

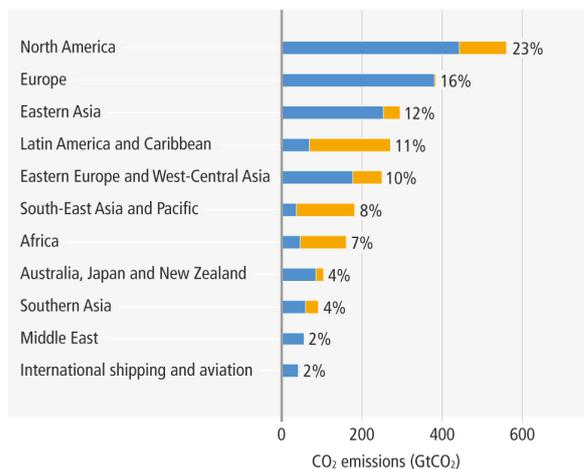
The bottom 50% of emitters spend less than USD3PPP per capita per day. The top 10% of emitters (an open-ended category) spend more than USD23PPP per capita per day. The wide range of estimates for the contribution of the top 10% result from the wide range of spending in this category and differing methods in the assessed literature. {Annex I: Glossary; 2.6}

B.3.5 At least 18 countries have sustained production-based GHG and consumption-based CO₂ emission reductions for longer than 10 years. Reductions were linked to energy supply decarbonisation, energy efficiency gains, and energy demand reduction, which resulted from both policies and changes in economic structure. Some countries have reduced production-based GHG emissions by a third or more since peaking, and some have achieved several years of consecutive reduction rates of around 4 %/yr, comparable to global reductions in scenarios limiting warming to 2°C (>67%) or lower. These reductions have only partly offset global emissions growth. (*high confidence*) (Figure SPM.2) {Figure TS.4, 2.2, 1.3.2}

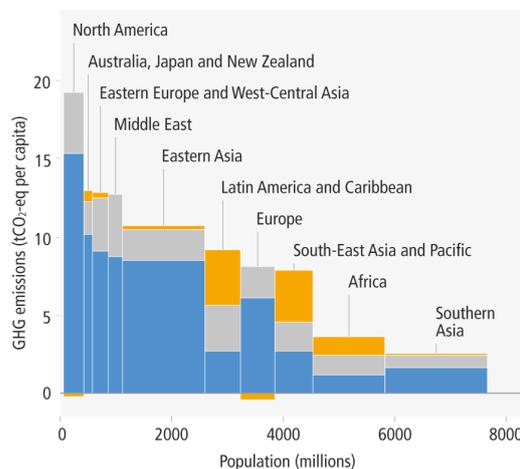
Emissions have grown in most regions but are distributed unevenly, both in the present day and cumulatively since 1850.



b. Historical cumulative net anthropogenic CO₂ emissions per region (1850–2019)



c. Net anthropogenic GHG emissions per capita and for total population, per region (2019)



d. Regional indicators (2019) and regional production vs consumption accounting (2018)

	Africa	Australia, Japan, New Zealand	Eastern Asia	Eastern Europe, West-Central Asia	Europe	Latin America and Caribbean	Middle East	North America	South-East Asia and Pacific	Southern Asia
Population (million persons, 2019)	1292	157	1471	291	620	646	252	366	674	1836
GDP per capita (USD1000 _{ppp} 2017 per person) ¹	5.0	43	17	20	43	15	20	61	12	6.2
Net GHG 2019² (production basis)										
% GHG contributions	9%	3%	27%	6%	8%	10%	5%	12%	9%	8%
GHG emissions intensity (tCO ₂ -eq / USD1000 _{ppp} 2017)	0.78	0.30	0.62	0.64	0.18	0.61	0.64	0.31	0.65	0.42
GHG per capita (tCO ₂ -eq per person)	3.9	13	11	13	7.8	9.2	13	19	7.9	2.6
CO₂FFI, 2018, per person										
Production-based emissions (tCO ₂ FFI per person, based on 2018 data)	1.2	10	8.4	9.2	6.5	2.8	8.7	16	2.6	1.6
Consumption-based emissions (tCO ₂ FFI per person, based on 2018 data)	0.84	11	6.7	6.2	7.8	2.8	7.6	17	2.5	1.5

¹ GDP per capita in 2019 in USD2017 currency purchasing power basis.

² Includes CO₂FFI, CO₂LULUCF and Other GHGs, excluding international aviation and shipping.

The regional groupings used in this figure are for statistical purposes only and are described in Annex II, Part I.

Figure SPM.2: Regional GHG emissions, and the regional proportion of total cumulative production-based CO₂ emissions from 1850–2019

Panel a shows global net anthropogenic GHG emissions by region (in GtCO₂-eq yr⁻¹ (GWP100 AR6)) for the time period 1990–2019 [FOOTNOTE 6]. Percentage values refer to the contribution of each region to total GHG emissions in each respective time period. The single year peak of emissions in 1997 was due to higher CO₂-LULUCF emissions from a forest and peat fire event in South East Asia. Regions are as grouped in Annex II.

Panel b shows the share of historical cumulative net anthropogenic CO₂ emissions per region from 1850 to 2019 in GtCO₂. This includes CO₂ from fossil fuel combustion and industrial processes (CO₂-FFI) and net CO₂ Land use, land use change, forestry (CO₂-LULUCF). Other GHG emissions are not included [FOOTNOTE 6]. CO₂-LULUCF emissions are subject to high uncertainties, reflected by a global uncertainty estimate of ± 70% (90% confidence interval).

Panel c shows the distribution of regional GHG emissions in tonnes CO₂-eq per capita by region in 2019. GHG emissions are categorised into: CO₂-FFI, net CO₂-LULUCF and other GHG emissions (methane, nitrous oxide, fluorinated gases, expressed in CO₂-eq using GWP100-AR6). The height of each rectangle shows per-capita emissions, the width shows the population of the region, so that the area of the rectangles refers to the total emissions for each region. Emissions from international aviation and shipping are not included. In the case of two regions, the area for CO₂-LULUCF is below the axis, indicating net CO₂ removals rather than emissions. CO₂-LULUCF emissions are subject to high uncertainties, reflected by a global uncertainty estimate of ± 70% (90% confidence interval).

Panel d shows population, GDP per person, emission indicators by region in 2019 for percentage GHG contributions, total GHG per person, and total GHG emissions intensity, together with production-based and consumption-based CO₂-FFI data, which is assessed in this report up to 2018. Consumption-based emissions are emissions released to the atmosphere in order to generate the goods and services consumed by a certain entity (e.g., region). Emissions from international aviation and shipping are not included. {1.3, Figure 1.2, 2.2, Figure 2.9, Figure 2.10, Figure 2.11, Annex II}

B.4 The unit costs of several low-emission technologies have fallen continuously since 2010. Innovation policy packages have enabled these cost reductions and supported global adoption. Both tailored policies and comprehensive policies addressing innovation systems have helped overcome the distributional, environmental and social impacts potentially associated with global diffusion of low-emission technologies. Innovation has lagged in developing countries due to weaker enabling conditions. Digitalisation can enable emission reductions, but can have adverse side-effects unless appropriately governed. (*high confidence*) (Figure SPM.3) {2.2, 6.3, 6.4, 7.2, 12.2, 16.2, 16.4, 16.5, Cross-Chapter Box 11 in Chapter 16}

B.4.1 From 2010–2019, there have been sustained decreases in the unit costs of solar energy (85%), wind energy (55%), and lithium-ion batteries (85%), and large increases in their deployment, e.g., >10x for solar and >100x for electric vehicles (EVs), varying widely across regions (Figure SPM.3). The mix of policy instruments which reduced costs and stimulated adoption includes public R&D, funding for demonstration and pilot projects, and demand pull instruments such as deployment subsidies to attain scale. In comparison to modular small-unit size technologies, the empirical record shows that multiple large-scale mitigation technologies, with fewer opportunities for learning, have seen minimal cost reductions and their adoption has grown slowly. (*high confidence*) {1.3, 1.5, Figure 2.5, 2.5, 6.3, 6.4, 7.2, 11.3, 12.2, 12.3, 12.6, 13.6, 16.3, 16.4, 16.6}

B.4.2 Policy packages tailored to national contexts and technological characteristics have been effective in supporting low-emission innovation and technology diffusion. Appropriately designed policies and governance have helped address distributional impacts and rebound effects. Innovation has provided opportunities to lower emissions and reduce emission growth and created social and environmental co-benefits. (*high confidence*) Adoption of low-emission technologies lags in most

developing countries, particularly least developed ones, due in part to weaker enabling conditions, including limited finance, technology development and transfer, and capacity. In many countries, especially those with limited institutional capacities, several adverse side-effects have been observed as a result of diffusion of low-emission technology, e.g., low-value employment, and dependency on foreign knowledge and suppliers. Low-emission innovation along with strengthened enabling conditions can reinforce development benefits, which can, in turn, create feedbacks towards greater public support for policy. (*medium confidence*) {9.9, 13.6, 13.7, 16.3, 16.4, 16.5, 16.6, Cross-Chapter Box 12 in Chapter 16, TS.3}

B.4.3 Digital technologies can contribute to mitigation of climate change and the achievement of several SDGs (*high confidence*). For example, sensors, Internet of Things, robotics, and artificial intelligence can improve energy management in all sectors, increase energy efficiency, and promote the adoption of many low-emission technologies, including decentralised renewable energy, while creating economic opportunities (*high confidence*). However, some of these climate change mitigation gains can be reduced or counterbalanced by growth in demand for goods and services due to the use of digital devices (*high confidence*). Digitalisation can involve trade-offs across several SDGs, e.g., increasing electronic waste, negative impacts on labour markets, and exacerbating the existing digital divide. Digital technology supports decarbonisation only if appropriately governed (*high confidence*). {5.3, 10, 12.6, 16.2, Cross-Chapter Box 11 in Chapter 16, TS.5, Box TS.14}

The unit costs of some forms of renewable energy and of batteries for passenger EVs have fallen, and their use continues to rise.

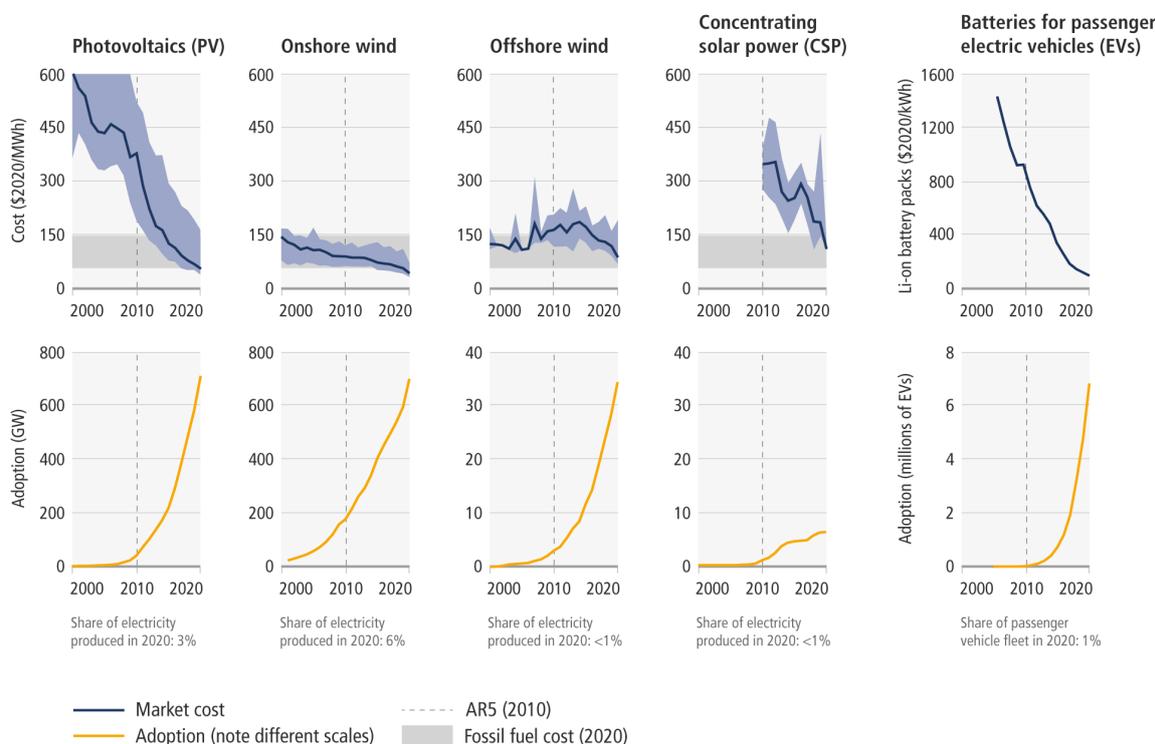


Figure SPM.3: Unit cost reductions and use in some rapidly changing mitigation technologies

The top panel shows global costs per unit of energy (USD/MWh) for some rapidly changing mitigation technologies. Solid blue lines indicate average unit cost in each year. Light blue shaded areas show the range between the 5th and 95th percentiles in each year. Grey shading indicates the range of unit costs for new fossil fuel (coal and gas) power in 2020 (corresponding to USD55–148 per MWh). In 2020, the levelised costs of energy (LCOE) of the four renewable energy technologies could compete with fossil fuels in many places. For batteries, costs shown are for 1 kWh of battery storage capacity; for the others, costs are LCOE, which includes installation, capital, operations, and maintenance costs per MWh of electricity produced. The literature uses LCOE because it allows consistent comparisons of cost trends across a diverse set of energy technologies to be made. However, it does not include the costs of grid integration or climate impacts. Further, LCOE does not take into account other environmental and social externalities that may modify the overall (monetary and non-monetary) costs of technologies and alter their deployment.

The bottom panel shows cumulative global adoption for each technology, in GW of installed capacity for renewable energy and in millions of vehicles for battery-electric vehicles. A vertical dashed line is placed in 2010 to indicate the change since AR5. Shares of electricity produced and share of passenger vehicle fleet are indicated in text for 2020 based on provisional data, i.e., percentage of total electricity production (for PV, onshore wind, offshore wind, CSP) and of total stock of passenger vehicles (for electric vehicles). The electricity production share reflects different capacity factors; e.g., for the same amount of installed capacity, wind produces about twice as much electricity as solar PV. {2.5, 6.4}

Renewable energy and battery technologies were selected as illustrative examples because they have recently shown rapid changes in costs and adoption, and because consistent data are available. Other mitigation options assessed in the report are not included as they do not meet these criteria.

B.5 There has been a consistent expansion of policies and laws addressing mitigation since AR5. This has led to the avoidance of emissions that would otherwise have occurred and increased investment in low-GHG technologies and infrastructure. Policy coverage of emissions is uneven across sectors. Progress on the alignment of financial flows towards the goals of the Paris Agreement remains slow and tracked climate finance flows are distributed unevenly across regions and sectors. (*high confidence*) {5.6, 13.2, 13.4, 13.5, 13.6, 13.9, 14.3, 14.4, 14.5, Cross-Chapter Box 10 in Chapter 14, 15.3, 15.5}

B.5.1 The Kyoto Protocol led to reduced emissions in some countries and was instrumental in building national and international capacity for GHG reporting, accounting and emissions markets (*high confidence*). At least 18 countries that had Kyoto targets for the first commitment period have had sustained absolute emission reductions for at least a decade from 2005, of which two were countries with economies in transition (*very high confidence*). The Paris Agreement, with near universal participation, has led to policy development and target-setting at national and sub-national levels, in particular in relation to mitigation, as well as enhanced transparency of climate action and support (*medium confidence*). {14.3, 14.6}

B.5.2 The application of diverse policy instruments for mitigation at the national and sub-national levels has grown consistently across a range of sectors (*high confidence*). By 2020, over 20% of global GHG emissions were covered by carbon taxes or emissions trading systems, although coverage and prices have been insufficient to achieve deep reductions (*medium confidence*). By 2020, there were ‘direct’ climate laws focused primarily on GHG reductions in 56 countries covering 53% of global emissions (*medium confidence*). Policy coverage remains limited for emissions from agriculture and

the production of industrial materials and feedstocks (*high confidence*). {5.6, 7.6, 11.5, 11.6, 13.2, 13.6}

B.5.3 In many countries, policies have enhanced energy efficiency, reduced rates of deforestation and accelerated technology deployment, leading to avoided and in some cases reduced or removed emissions (*high confidence*). Multiple lines of evidence suggest that mitigation policies have led to avoided global emissions of several Gt CO₂.eq yr⁻¹ (*medium confidence*). At least 1.8 Gt CO₂.eq yr⁻¹ can be accounted for by aggregating separate estimates for the effects of economic and regulatory instruments. Growing numbers of laws and executive orders have impacted global emissions and were estimated to result in 5.9 Gt CO₂.eq yr⁻¹ less in 2016 than they otherwise would have been. (*medium confidence*) (Figure SPM.3) {2.2, 2.8, 6.7, 7.6, 9.9, 10.8, 13.6, Cross-chapter Box 10 in Chapter 14}

B.5.4 Annual tracked total financial flows for climate mitigation and adaptation increased by up to 60% between 2013/14 and 2019/20 (in USD2015), but average growth has slowed since 2018²³ (*medium confidence*). These financial flows remained heavily focused on mitigation, are uneven, and have developed heterogeneously across regions and sectors (*high confidence*). In 2018, public and publicly mobilised private climate finance flows from developed to developing countries were below the collective goal under the UNFCCC and Paris Agreement to mobilize USD 100 billion per year by 2020 in the context of meaningful mitigation action and transparency on implementation (*medium confidence*). Public and private finance flows for fossil fuels are still greater than those for climate adaptation and mitigation (*high confidence*). Markets for green bonds, ESG (environmental, social and governance) and sustainable finance products have expanded significantly since AR5. Challenges remain, in particular around integrity and additionality, as well as the limited applicability of these markets to many developing countries. (*high confidence*) {Box 15.4, 15.3, 15.5, 15.6, Box 15.7}

FOOTNOTE 23: Estimates of financial flows (comprising both private and public, domestic and international flows) are based on a single report which assembles data from multiple sources and which has applied various changes to their methodology over the past years. Such data can suggest broad trends but is subject to uncertainties.

B.6 Global GHG emissions in 2030 associated with the implementation of nationally determined contributions (NDCs) announced prior to COP26 [FOOTNOTE 24] would make it *likely* that warming will exceed 1.5°C during the 21st century.[FOOTNOTE 25] *Likely* limiting warming to below 2°C would then rely on a rapid acceleration of mitigation efforts after 2030. Policies implemented by the end of 2020 [FOOTNOTE 26] are projected to result in higher global GHG emissions than those implied by NDCs. (*high confidence*) (Figure SPM.4) {3.3, 3.5, 4.2, Cross-Chapter Box 4 in Chapter 4}

FOOTNOTE 24: NDCs announced prior to COP26 refer to the most recent nationally determined contributions submitted to the UNFCCC up to the literature cut-off date of this report, 11 October 2021, and revised NDCs announced by China, Japan and the Republic of Korea prior to October 2021 but only submitted thereafter. 25 NDC updates were submitted between 12 October 2021 and prior to the start of COP26.

FOOTNOTE 25: This implies that mitigation after 2030 can no longer establish a pathway with less than 67% probability to exceed 1.5°C during the 21st century, a defining feature of the class of pathways that limit warming to 1.5°C (>50%) with no or limited overshoot assessed in this report (Category C1 in Table SPM.1). These pathways limit warming to 1.6°C or lower throughout the 21st century with a 50% likelihood.

FOOTNOTE 26: The policy cut-off date in studies used to project GHG emissions of “policies implemented by the end of 2020” varies between July 2019 and November 2020. {Table 4.2}

B.6.1 Policies implemented by the end of 2020 are projected to result in higher global GHG emissions than those implied by NDCs, indicating an implementation gap. A gap remains between global GHG emissions in 2030 associated with the implementation of NDCs announced prior to COP26 and those associated with modelled mitigation pathways assuming immediate action (for quantification see Table SPM.X). [FOOTNOTE 27] The magnitude of the emission gap depends on the global warming level considered and whether only unconditional or also conditional elements of NDCs [FOOTNOTE 28] are considered.[FOOTNOTE 29] (*high confidence*) {3.5, 4.2, Cross-Chapter Box 4 in Chapter 4}

Table SPM.X: Projected global emissions in 2030 associated with policies implemented by the end of 2020 and NDCs announced prior to COP26, and associated emission gaps. *Emissions projections for 2030 and absolute differences in emissions are based on emissions of 52-56 GtCO₂-eq yr⁻¹ in 2019 as assumed in underlying model studies. (*medium confidence*) {4.2, Table 4.3, Cross-Chapter Box 4 in Chapter 4}

GtCO ₂ -eq yr ⁻¹	Implied by policies implemented by the end of 2020	Implied by NDCs announced prior to COP26	
		Unconditional elements	Inc. conditional elements
Median (Min–Max)*	57 (52–60)	53 (50–57)	50 (47–55)
Implementation gap between implemented policies and NDCs (Median)		4	7
Emission gap between NDCs and pathways that limit warming to 2°C (>67%) with immediate action		10–16	6–14
Emissions gap between NDCs and pathways that limit warming to 1.5°C (>50%) with no or limited overshoot with immediate action		19–26	16–23

FOOTNOTE 27: Immediate action in modelled global pathways refers to the adoption between 2020 and at latest before 2025 of climate policies intended to limit global warming to a given level. Modelled

pathways that limit warming to 2°C (>67%) based on immediate action are summarised in Category C3a in Table SPM.1. All assessed modelled global pathways that limit warming to 1.5°C (>50%) with no or limited overshoot assume immediate action as defined here (Category C1 in Table SPM.1).

FOOTNOTE 28: In this report, “unconditional” elements of NDCs refer to mitigation efforts put forward without any conditions. “Conditional” elements refer to mitigation efforts that are contingent on international cooperation, for example bilateral and multilateral agreements, financing or monetary and/or technological transfers. This terminology is used in the literature and the UNFCCC’s NDC Synthesis Reports, not by the Paris Agreement. {4.2.1, 14.3.2}

FOOTNOTE 29: Two types of gaps are assessed: The implementation gap is calculated as the difference between the median of global emissions in 2030 implied by policies implemented by the end of 2020 and those implied by NDCs announced prior to COP26. The emissions gap is calculated as the difference between GHG emissions implied by the NDCs (minimum/maximum emissions in 2030) and the median of global GHG emissions in modelled pathways limiting warming to specific levels based on immediate action and with stated likelihoods as indicated (Table SPM.1).

B.6.2 Global emissions in 2030 associated with the implementation of NDCs announced prior to COP26 are lower than the emissions implied by the original NDCs [FOOTNOTE 30] (*high confidence*). The original emission gap has fallen by about 20% to one third relative to pathways that limit warming to 2°C (>67%) with immediate action (Category C3a in Table SPM.1), and by about 15-20% relative to pathways limiting warming to 1.5°C (>50%) with no or limited overshoot (Category C1 in Table SPM.1) (*medium confidence*). (Figure SPM.4) {3.5, 4.2, Cross-Chapter Box 4 in Chapter 4}

FOOTNOTE 30: Original NDCs refer to those submitted to the UNFCCC in 2015 and 2016. Unconditional elements of NDCs announced prior to COP26 imply global GHG emissions in 2030 that are 3.8 [3.0–5.3] GtCO₂-eq yr⁻¹ lower than those from the original NDCs, and 4.5 [2.7–6.3] GtCO₂-eq yr⁻¹ lower when conditional elements of NDCs are included. NDC updates at or after COP26 could further change the implied emissions.

B.6.3 Modelled global emission pathways consistent with NDCs announced prior to COP26 that limit warming to 2°C (>67%) (Category C3b in Table SPM.1) imply annual average global GHG emissions reduction rates of 0–0.7 GtCO₂-eq per year during the decade 2020-2030, with an unprecedented acceleration to 1.4–2.0 GtCO₂-eq per year during 2030-2050 (*medium confidence*). Continued investments in unabated high emitting infrastructure and limited development and deployment of low emitting alternatives prior to 2030 would act as barriers to this acceleration and increase feasibility risks (*high confidence*). {3.3, 3.5, 3.8, Cross-Chapter Box 5 in Chapter 4}

B.6.4 Modelled global emission pathways consistent with NDCs announced prior to COP26 will *likely* exceed 1.5°C during the 21st century. Those pathways that then return warming to 1.5°C by 2100 with a likelihood of 50% or greater imply a temperature overshoot of 0.15-0.3°C (42 pathways in category C2 in Table SPM.1). In such pathways, global cumulative net-negative CO₂ emissions are -380 [-860 to -200] GtCO₂ [FOOTNOTE 31] in the second half of the century, and there is a rapid acceleration of other mitigation efforts across all sectors after 2030. Such overshoot pathways imply increased climate-related risk, and are subject to increased feasibility concerns[FOOTNOTE 32], and greater social and environmental risks, compared to pathways that limit warming to 1.5°C (>50%) with no or limited overshoot. (*high confidence*) (Figure SPM.4, Table SPM.1) {3.3, 3.5, 3.8, 12.3; WG II SPM.B.6}

FOOTNOTE 31: Median and very likely range [5th to 95th percentile].

FOOTNOTE 32: Returning to below 1.5°C in 2100 from GHG emissions levels in 2030 associated with the implementation of NDCs is infeasible for some models due to model-specific constraints on the deployment of mitigation technologies and the availability of net negative CO₂ emissions.

Projected global GHG emissions from NDCs announced prior to COP26 would make it likely that warming will exceed 1.5°C and also make it harder after 2030 to limit warming to below 2°C.

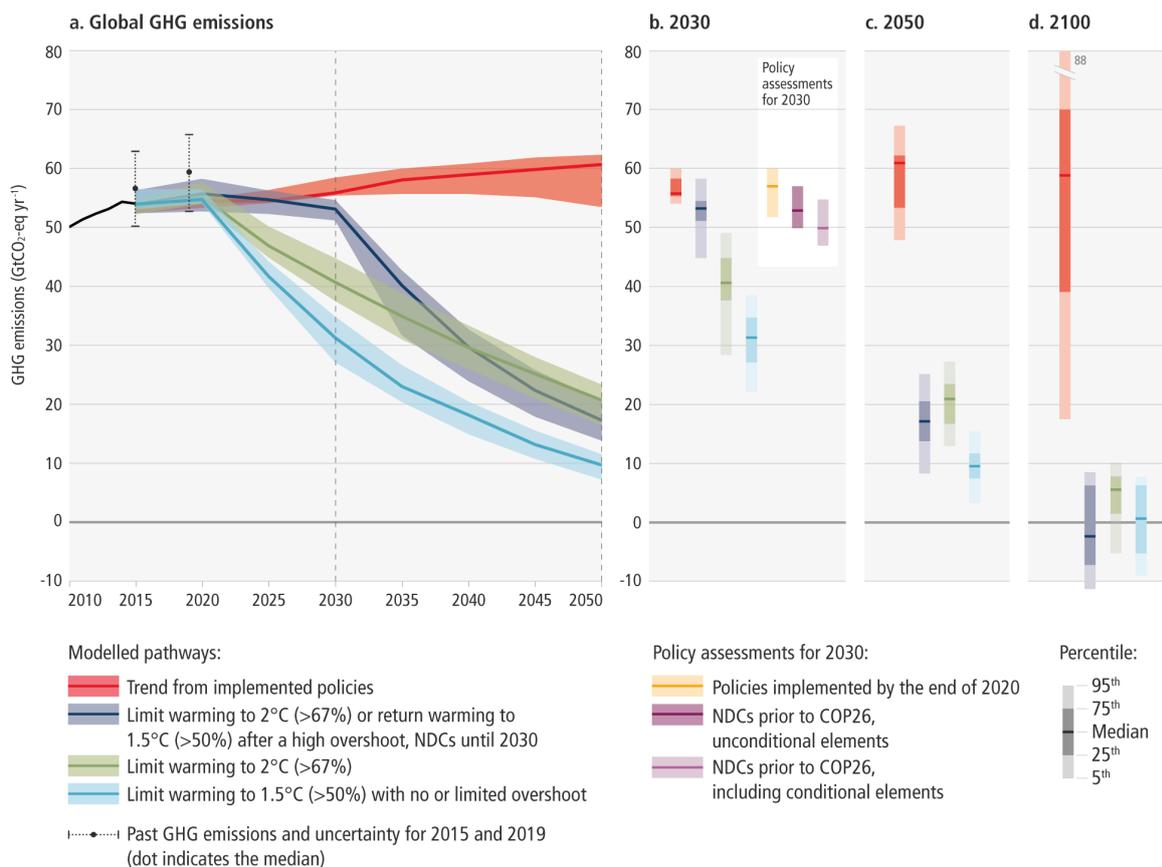


Figure SPM.4: Global GHG emissions of modelled pathways (funnels in Panel a. and associated bars in Panels b, c, d) and projected emission outcomes from near-term policy assessments for 2030 (Panel b).

Panel a shows global GHG emissions over 2015-2050 for four types of assessed modelled global pathways:

- Trend from implemented policies: Pathways with projected near-term GHG emissions in line with policies implemented until the end of 2020 and extended with comparable ambition levels beyond 2030 (29 scenarios across categories C5-C7, Table SPM.1)
- Limit to 2°C (>67%) or return warming to 1.5°C (>50%) after a high overshoot, NDCs until 2030: Pathways with GHG emissions until 2030 associated with the implementation of NDCs announced prior to COP26, followed by accelerated emissions reductions *likely* to limit warming to 2°C (C3b, Table SPM.1) or to return warming to 1.5°C with a probability of 50% or greater after high overshoot (subset of 42 scenarios from C2, Table SPM.1).

- Limit to 2°C (>67%) with immediate action: Pathways that limit warming to 2°C (>67%) with immediate action after 2020²⁷ (C3a, Table SPM.1).
- Limit to 1.5°C (>50%) with no or limited overshoot: Pathways limiting warming to 1.5°C with no or limited overshoot (C1, Table SPM.1 C1). All these pathways assume immediate action after 2020.

Past GHG emissions for 2010-2015 used to project global warming outcomes of the modelled pathways are shown by a black line [FOOTNOTE 33] and past global GHG emissions in 2015 and 2019 as assessed in Chapter 2 are shown by whiskers.

FOOTNOTE 33: See the Box SPM.1 for a description of the approach to project global warming outcomes of modelled pathways and its consistency between the climate assessment in AR6 WG I.

Panels b, c and d show snapshots of the GHG emission ranges of the modelled pathways in 2030, 2050, and 2100, respectively. Panel b also shows projected emissions outcomes from near-term policy assessments in 2030 from Chapter 4.2 (Tables 4.2 and 4.3; median and full range). GHG emissions are in CO₂-equivalent using GWP100 from AR6 WG I. {3.5, 4.2, Tables 4.2 and 4.3, Cross-Chapter Box 4 in Chapter 4}

B.7 Projected cumulative future CO₂ emissions over the lifetime of existing and currently planned fossil fuel infrastructure without additional abatement exceed the total cumulative net CO₂ emissions in pathways that limit warming to 1.5°C (>50%) with no or limited overshoot. They are approximately equal to total cumulative net CO₂ emissions in pathways that limit warming to 2°C (>67%). (*high confidence*) {2.7, 3.3}

B.7.1 If historical operating patterns are maintained, [FOOTNOTE 34] and without additional abatement [FOOTNOTE 35], estimated cumulative future CO₂ emissions from existing fossil fuel infrastructure, the majority of which is in the power sector, would, from 2018 until the end of its lifetime, amount to 660 [460–890] GtCO₂. They would amount to 850 [600–1100] GtCO₂ when unabated emissions from currently planned infrastructure in the power sector is included. These estimates compare with cumulative global net CO₂ emissions from all sectors of 510 [330–710] GtCO₂ until the time of reaching net zero CO₂ emissions [FOOTNOTE 36] in pathways that limit warming to 1.5°C (>50%) with no or limited overshoot, and 890 [640–1160] GtCO₂ in pathways that limit warming to 2°C (>67%). (Table SPM.1) (*high confidence*) {2.7, Figure 2.26, Figure TS.8}

FOOTNOTE 34: Historical operating patterns are described by load factors and lifetimes of fossil fuel installations as observed in the past (average and range).

FOOTNOTE 35: Abatement here refers to human interventions that reduce the amount of greenhouse gases that are released from fossil fuel infrastructure to the atmosphere.

FOOTNOTE 36: Total cumulative CO₂ emissions up to the time of global net zero CO₂ emissions are similar but not identical to the remaining carbon budget for a given temperature limit assessed by Working Group I. This is because the modelled emission scenarios assessed by Working Group III cover a range of temperature levels up to a specific limit, and exhibit a variety of reductions in non-CO₂ emissions that also contribute to overall warming. {Box 3.4}

B.7.2 In modelled global pathways that limit warming to 2°C (>67%) or lower, most remaining fossil fuel CO₂ emissions until the time of global net zero CO₂ emissions are projected to occur outside the power sector, mainly in industry and transport. Decommissioning and reduced utilisation of existing

fossil fuel based power sector infrastructure, retrofitting existing installations with CCS [FOOTNOTE 37] switches to low carbon fuels, and cancellation of new coal installations without CCS are major options that can contribute to aligning future CO₂ emissions from the power sector with emissions in the assessed global modelled least-cost pathways. The most appropriate strategies will depend on national and regional circumstances, including enabling conditions and technology availability. (*high confidence*) {Table 2.7, 2.7, 3.4, 6.3, 6.5, 6.7, Box SPM.1}

FOOTNOTE 37: In this context, capture rates of new installations with CCS are assumed to be 90-95% + {11.3.5}. Capture rates for retrofit installations can be comparable, if plants are specifically designed for CCS retrofits {11.3.6}.

C. System transformations to limit global warming

C.1 Global GHG emissions are projected to peak between 2020 and at the latest before 2025 in global modelled pathways that limit warming to 1.5°C (>50%) with no or limited overshoot and in those that limit warming to 2°C (>67%) and assume immediate action. [Table SPM footnote [#9], FOOTNOTE 38] **In both types of modelled pathways, rapid and deep GHG emissions reductions follow throughout 2030, 2040 and 2050 (*high confidence*). Without a strengthening of policies beyond those that are implemented by the end of 2020, GHG emissions are projected to rise beyond 2025, leading to a median global warming of 3.2 [2.2 to 3.5] °C by 2100 [FOOTNOTE 39, 40] (*medium confidence*). (Table SPM.1, Figure SPM.4, Figure SPM.5) {3.3, 3.4}**

FOOTNOTE 38: All reported warming levels are relative to the period 1850–1900. If not otherwise specified, ‘pathways’ always refer to pathways computed with a model. Immediate action in the pathways refers to the adoption of climate policies between 2020 and at latest 2025 intended to limit global warming at a given level.

FOOTNOTE 39: Long-term warming is calculated from all modelled pathways assuming mitigation efforts consistent with national policies that were implemented by the end of 2020 (scenarios that fall into policy category P1b of Chapter 3) and that pass through the 2030 GHG emissions ranges of such pathways assessed in Chapter 4 (See FOOTNOTE 25) {3.2, Table 4.2}

FOOTNOTE 40: Warming estimates refer to the 50th and [5th–95th] percentile across the modelled pathways and the median temperature change estimate of the probabilistic WG I climate model emulators[Footnote 1¹ (Table SPM1).

C.1.1 Net global GHG emissions are projected to fall from 2019 levels by 27% [13–45%] by 2030 and 63% [52–76%] [FOOTNOTE 41] by 2050 in global modelled pathways that limit warming to 2°C (>67%) and assuming immediate action (category C3a, Table SPM.1). This compares with reductions of 43% [34–60%] by 2030 and 84% [73–98%] by 2050 in pathways that limit warming to 1.5°C (>50%) with no or limited overshoot (C1, Table SPM.1) (*high confidence*). [FOOTNOTE 42] In modelled pathways that return warming to 1.5°C (>50%) after a high overshoot [FOOTNOTE 43], GHG emissions are reduced by 23 [0–44%] in 2030 and by 75 [62–91%] in 2050 (C2, Table SPM.1) (*high confidence*). Modelled pathways that are consistent with NDCs announced prior to COP26 until 2030 and assume no increase in ambition thereafter have higher emissions, leading to a median global warming of 2.8°C [2.1–3.4°C] by 2100 (*medium confidence*). [FOOTNOTE 24] (Figure SPM .4). {3.3}

FOOTNOTE 41: In this report, emissions reductions are reported relative to 2019 modelled emission levels, while in SR1.5 emissions reductions were calculated relative to 2010. Between 2010 and 2019 global GHG and global CO₂ emissions have grown by 12% (6.5 GtCO₂eq) and 13% (5.0 Gt CO₂) respectively. In global modelled pathways assessed in this report that limit warming to 1.5°C (>50%) with no or limited overshoot, GHG emissions are projected to be reduced by 37% [28–57%] in 2030 relative to 2010. In the same type of pathways assessed in SR1.5, GHG emissions are reduced by 45% (40–60% interquartile range) relative to 2010. In absolute terms, the 2030 GHG emissions levels of pathways that limit warming to 1.5°C (>50%) with no or limited overshoot are higher in AR6 (31 [21–36] GtCO₂eq) than in SR1.5 (28 (26–31 interquartile range) GtCO₂eq). (Figure SPM. 1, Table SPM.1) {3.3, SR1.5}

FOOTNOTE 42: Scenarios in this category limit peak warming to 2°C throughout the 21st century with close to, or more than, 90% likelihood.

FOOTNOTE 43: This category contains 91 scenarios with immediate action and 42 scenarios that are consistent with the NDCs until 2030.

C.1.2 In modelled pathways that limit warming to 2°C (>67%) assuming immediate action, global net CO₂ emissions are reduced compared to modelled 2019 emissions by 27% [11–46%] in 2030 and by 52% [36–70%] in 2040; and global CH₄ emissions are reduced by 24% [9–53%] in 2030 and by 37% [20–60%] in 2040. In pathways that limit warming to 1.5°C (>50%) with no or limited overshoot global net CO₂ emissions are reduced compared to modelled 2019 emissions by 48% [36–69%] in 2030 and by 80% [61–109%] in 2040; and global CH₄ emissions are reduced by 34% [21–57%] in 2030 and 44% [31–63%] in 2040. There are similar reductions of non-CO₂ emissions by 2050 in both types of pathways: CH₄ is reduced by 45% [25–70%]; N₂O is reduced by 20% [-5 – 55%]; and F-Gases are reduced by 85% [20–90%]. [FOOTNOTE 44] Across most modelled pathways, this is the maximum technical potential for anthropogenic CH₄ reductions in the underlying models (*high confidence*). Further emissions reductions, as illustrated by the IMP-SP pathway, may be achieved through changes in activity levels and/or technological innovations beyond those represented in the majority of the pathways (*medium confidence*). Higher emissions reductions of CH₄ could further reduce peak warming. (*high confidence*) (Figure SPM.5) {3.3}

FOOTNOTE 44: These numbers for CH₄, N₂O, and F-gases are rounded to the nearest 5% except numbers below 5%.

C.1.3 In modelled pathways consistent with the continuation of policies implemented by the end of 2020, GHG emissions continue to rise, leading to global warming of 3.2 [2.2–3.5]°C by 2100 (within C5-C7, Table SPM.1) (*medium confidence*). Pathways that exceed warming of >4°C (≥50%) (C8, SSP5-8.5, Table SPM.1) would imply a reversal of current technology and/or mitigation policy trends (*medium confidence*). Such warming could occur in emission pathways consistent with policies implemented by the end of 2020 if climate sensitivity is higher than central estimates (*high confidence*). (Table SPM.1, Figure SPM.4) {3.3, Box 3.3}

C.1.4 Global modelled pathways falling into the lowest temperature category of the assessed literature (C1, Table SPM.1) are on average associated with a higher median peak warming in AR6 compared to pathways in the same category in SR1.5. In the modelled pathways in AR6, the likelihood of limiting warming to 1.5°C has on average declined compared to SR1.5. This is because GHG emissions have risen since 2017, and many recent pathways have higher projected emissions by 2030, higher cumulative net CO₂ emissions and slightly later dates for reaching net zero CO₂ or net zero GHG emissions. High mitigation challenges, for example, due to assumptions of slow technological change, high levels of global population growth, and high fragmentation as in the Shared Socioeconomic Pathway SSP3, may render modelled pathways that limit warming to 2°C (> 67%) or lower infeasible. (*medium confidence*) (Table SPM.1, Box SPM.1) {3.3, 3.8, Annex III Figure II.1, Annex III Figure II.3}

Table SPM.1 | Key characteristics of the modelled global emissions pathways: Summary of projected CO₂ and GHG emissions, projected net zero timings and the resulting global warming outcomes. Pathways are categorised (rows), according to their likelihood of limiting warming to different peak warming levels (if peak temperature occurs before 2100) and 2100 warming levels.

Values shown are for the median [p50] and 5th-95th percentiles [p5-p95], noting that not all pathways achieve net zero CO₂ or GHGs.

APPROVED

Summary for Policymakers

IPCC AR6 WG III

p50 [p25-p95] ⁽¹⁾		GHG emissions Gt CO ₂ -eq/yr ⁽²⁾			GHG emissions reductions from 2019 % ⁽³⁾			Emissions milestones ^{(6),(8)}				Cumulative CO ₂ emissions Gt CO ₂ ⁽¹³⁾		Cumulative net-negative CO ₂ emissions Gt CO ₂	Global mean temperature change 50% probability ⁽¹⁶⁾ °C		Likelihood of peak global warming staying below (%) ⁽¹⁵⁾		
Category ⁽⁴⁾ [Category / subset label # pathways]	WG I SSP & WG III IP2/TMP2 alignment ⁽⁵⁾	2030	2040	2050	2030	2040	2050	Peak CO ₂ emissions (% peak before 2100)	Peak GHG emissions (% peak before 2100)	Net-zero CO ₂ (% net-zero pathways)	Net-zero GHGs ⁽¹¹⁾ (% net-zero pathways)	2020 to net-zero CO ₂	2020-2100	Year of net-zero CO ₂ to 2100	at peak warming	2100	-1.5°C	-2.0°C	-3.0°C
		<p><i>Modelled global emissions pathways categorised by projected global warming levels (GWL). Detailed likelihood definitions are provided in SPM Box 1. The five illustrative scenarios (SSP2-4.5) considered by AR6 WGI and the Illustrative Mitigation Pathways assessed in WGIII are aligned with the temperature categories and are indicated in a separate column. Global emission pathways contain regionally differentiated information. This assessment focuses on their global characteristics.</i></p> <p><i>Projected median annual GHG emissions in the year across the scenarios, with the 5th-95th percentile in brackets. Modelled GHG emissions in 2019: 55 [53-58] Gt CO₂-eq</i></p> <p><i>Projected median GHG emissions reductions of pathways in the year across the scenarios compared to modelled 2019, with the 5th-95th percentile in brackets. Negative numbers indicate increase in emissions compared to 2019</i></p> <p><i>Median 5-year intervals at which projected CO₂ & GHG emissions peak with the 5th-95th percentile interval in square brackets. Percentage of peaking pathways is denoted in round brackets. Three dots (...) denotes emissions peak in 2100 or beyond for that percentile.</i></p> <p><i>Median 5-year intervals at which pathways in this category reach net-zero, with the 5th-95th percentile interval in square brackets. Percentage of net zero pathways is denoted in round brackets. Three dots (...) denotes net zero not reached for that percentile.</i></p> <p><i>Median cumulative net CO₂ emissions across the projected scenarios in this category until reaching net-zero or until 2100, with the 5th-95th percentile interval in square brackets.</i></p> <p><i>Median cumulative net-negative CO₂ emissions between the year of net-zero CO₂ and 2100. More net-negative results in greater temperature declines after peak</i></p> <p><i>Projected temperature change of pathways in this category (50% probability across the range of climate uncertainties) relative to 1850-1900, at peak warming and in 2100, for the median value across the scenarios and the 5th-95th percentile interval in square brackets.</i></p> <p><i>Median likelihood that the projected pathways in this category stay below a given global warming level, with the 5th-95th percentile interval in square brackets.</i></p>																	
C1 [97]	limit warming to 1.5°C (>50%) with no or limited overshoot	31 [21-36]	17 [6-23]	9 [1-15]	43 [34-60]	69 [58-90]	84 [73-98]			2095-2100 (52%) [2050-...]	510 [330-710]	320 [-210-570]	-220 [-660-20]	1.6 [1.4-1.6]	1.3 [1.1-1.5]	38 [33-58]	90 [86-97]	100 [99-100]	
C1a [50]	... with net-zero GHGs	33 [22-37]	18 [6-24]	8 [0-15]	41 [31-59]	66 [58-89]	85 [72-100]	2020-2025 (100%) [2020-2025]	2050-2055 (100%) [2035-2070]	2070-2075 (100%) [2050-2090]	550 [340-760]	160 [-220-620]	-360 [-680-140]	1.6 [1.4-1.6]	1.2 [1.1-1.4]	38 [34-60]	90 [85-98]	100 [99-100]	
C1b [47]	... without net-zero GHGs	29 [21-36]	16 [7-21]	9 [4-13]	48 [35-61]	70 [62-87]	84 [76-93]			... (0%) [...-...]	460 [320-590]	360 [10-540]	-60 [-440-0]	1.6 [1.5-1.6]	1.4 [1.3-1.5]	37 [33-56]	89 [87-96]	100 [99-100]	
C2 [133]	return warming to 1.5°C (>50%) after a high overshoot	42 [31-55]	25 [17-34]	14 [5-21]	23 [0-44]	55 [40-71]	75 [62-91]	2020-2025 (100%) [2020-2030]	2055-2060 (100%) [2045-2070]	2070-2075 (87%) [2055-...]	720 [530-930]	400 [-90-620]	-360 [-680-60]	1.7 [1.5-1.8]	1.4 [1.2-1.5]	24 [15-42]	82 [71-93]	100 [99-100]	
C3 [311]	limit warming to 2°C (>67%)	44 [32-55]	29 [20-36]	20 [13-26]	21 [1-42]	46 [34-63]	64 [53-77]	2020-2025 (100%) [2020-2030]	2070-2075 (93%) [2055-...]	... (30%) [2075-...]	890 [640-1160]	800 [510-1140]	-40 [-290-0]	1.7 [1.6-1.8]	1.5 [1.5-1.8]	20 [13-41]	76 [68-91]	99 [98-100]	
C3a [204]	... with action starting in 2020	40 [30-49]	29 [21-36]	20 [14-27]	27 [13-45]	47 [35-63]	63 [52-76]	2020-2025 (100%) [2020-2025]	2070-2075 (91%) [2055-...]	... (24%) [2080-...]	860 [640-1180]	790 [480-1150]	-30 [-280-0]	1.7 [1.6-1.8]	1.6 [1.5-1.8]	21 [14-42]	78 [69-91]	100 [98-100]	
C3b [97]	... NDCs until 2030	52 [47-56]	29 [20-36]	18 [10-25]	5 [0-14]	46 [34-63]	68 [56-82]			2065-2070 (97%) [2055-2090]	910 [720-1150]	800 [560-1050]	-60 [-300-0]	1.8 [1.6-1.8]	1.6 [1.5-1.7]	17 [12-35]	73 [67-87]	99 [98-99]	
C4 [159]	limit warming to 2°C (>50%)	50 [41-56]	38 [28-44]	28 [19-35]	10 [0-27]	31 [20-50]	49 [35-65]	2020-2025 (100%) [2020-2030]	2080-2085 (86%) [2065-...]	... (31%) [2075-...]	1210 [970-1490]	1160 [700-1490]	-30 [-390-0]	1.9 [1.7-2.0]	1.8 [1.5-2.0]	11 [7-22]	59 [50-77]	98 [95-99]	
C5 [212]	limit warming to 2.5°C (>50%)	52 [46-56]	45 [37-53]	39 [30-49]	6 [1-18]	18 [4-33]	29 [11-48]			... (41%) [2080-...]	1780 [1400-2360]	1780 [1260-2360]	0 [-160-0]	2.2 [1.9-2.5]	2.1 [1.9-2.5]	4 [0-10]	37 [18-59]	91 [83-98]	
C6 [97]	limit warming to 3°C (>50%)	54 [50-62]	53 [48-61]	52 [45-57]	2 [-10-11]	3 [-14-14]	5 [-2-18]	2030-2035 (96%) [2020-2090]	2020-2025 (97%) [2020-2090]		2790 [2440-3520]				2.7 [2.4-2.9]	2.7 [2-18]	8 [0-2]	71 [53-88]	
C7 [164]	limit warming to 4°C (>50%)	62 [53-69]	67 [56-78]	70 [58-83]	-11 [-18-3]	-19 [-31-1]	-24 [-41-2]	2085-2090 (57%) [2040-...]	2090-2095 (56%) [2040-...]	no net-zero	no net-zero	4220 [3160-5000]		no net-zero	temperature does not peak by 2100	3.5 [2.8-3.9]	0 [0-0]	22 [7-60]	
C8 [29]	exceed warming of 4°C (>>50%)	71 [69-81]	80 [78-96]	88 [82-112]	-20 [-34-17]	-35 [-66-29]	-46 [-92-36]	2080-2085 (90%) [2070-...]			5600 [4910-7450]				4.2 [3.7-5.0]	0 [0-0]	4 [0-1]		

1 Values in the table refer to the 50th and [5th–95th] percentile values across the pathways falling within a given category as defined in Box SPM.1. For emissions-related columns these values relate to the distribution of all the pathways in that category. Harmonized emissions values are given for consistency with projected global warming outcomes using climate emulators. Based on the assessment of climate emulators in AR6 WG I (Chapter 7, Box 7.1), two climate emulators are used for the probabilistic assessment of the resulting warming of the pathways. For the ‘Temperature Change’ and ‘Likelihood’ columns, the single upper row values represent the 50th percentile across the pathways in that category and the median [50th percentile] across the warming estimates of the probabilistic MAGICC climate model emulator. For the bracketed ranges, the median warming for every pathway in that category is calculated for each of the two climate model emulators (MAGICC and FaIR). Subsequently, the 5th and 95th percentile values across all pathways for each emulator are calculated. The coolest and warmest outcomes (i.e. the lowest p5 of two emulators, and the highest p95, respectively) are shown in square brackets. These ranges therefore cover both the uncertainty of the emissions pathways as well as the climate emulators’ uncertainty.

2 For a description of pathways categories see Box SPM.1.

3 All global warming levels are relative to 1850–1900. See Table SPM 1 Footnote 13 below and SPM Scenarios Box FOOTNOTE 46 for more details.

4 C3 pathways are sub-categorised according to the timing of policy action to match the emissions pathways in Figure SPM.4. Two pathways derived from a cost-benefit analysis have been added to C3a, whilst 10 pathways with specifically designed near-term action until 2030, whose emissions fall below those implied by NDCs announced prior to COP26, are not included in either of the two subsets.

5 Alignment with the categories of the illustrative SSP scenarios considered in AR6 WG I, and the Illustrative (Mitigation) Pathways (IPs/IMPs) of WG III. The IMPs have common features such as deep and rapid emissions reductions, but also different combinations of sectoral mitigation strategies. See SPM Box 1 for an introduction of the IPs and IMPs and Chapter 3 for full descriptions. {3.2, 3.3, Annex III.II.4}

6 The Illustrative Mitigation Pathway ‘Neg’ has extensive use of carbon dioxide removal (CDR) in the AFOLU, energy and the industry sectors to achieve net negative emissions. Warming peaks around 2060 and declines to below 1.5°C (50% likelihood) shortly after 2100. Whilst technically classified as C3, it strongly exhibits the characteristics of C2 high overshoot pathways, hence it has been placed in the C2 category. See SPM C3.1 for an introduction of the IPs and IMPs.

7 The 2019 range of harmonized GHG emissions across the pathways [53–58 GtCO₂eq] is within the uncertainty ranges of 2019 emissions assessed in Chapter 2 [53–66 GtCO₂-eq]. {Fig SPM 1, Fig SPM 2, Box SPM1 FOOTNOTE 50}

8 Rates of global emission reduction in mitigation pathways are reported on a pathway-by-pathway basis relative to harmonized modelled global emissions in 2019 rather than the global emissions reported in SPM Section B and Chapter 2; this ensures internal consistency in assumptions about emission sources and activities, as well as consistency with temperature projections based on the physical climate science assessment by WG I. {Annex III.II.2.5, FOOTNOTE 50} Negative values (e.g., in C7, C8) represent an increase in emissions.

9 Emissions milestones are provided for 5-year intervals in order to be consistent with the underlying 5-year time-step data of the modelled pathways. Peak emissions (CO₂ and GHGs) are assessed for 5 year reporting intervals starting in 2020. The interval 2020–2025 signifies that projected emissions peak as soon as possible between 2020 and at latest before 2025. The upper 5-year interval refers to the median interval within which the emissions peak or reach net zero. Ranges in square brackets underneath refer to the range across the pathways, comprising the lower bound of the 5th percentile 5-year interval and the upper bound of the 95th percentile 5-year interval. Numbers in round brackets signify the fraction of pathways that reach specific milestones.

10 Percentiles reported across all pathways in that category include those that do not reach net zero before 2100 (fraction of pathways reaching net zero is given in round brackets). If the fraction of pathways that reach net zero before 2100 is lower than the fraction of pathways covered by a percentile (e.g., 0.95 for the 95th percentile), the percentile is not defined and denoted with "...". The fraction of pathways reaching net zero includes all with reported non-harmonised, and / or harmonised emissions profiles that reach net zero. Pathways were counted when at least one of the two profiles fell below 100 MtCO₂ yr⁻¹ until 2100.

11 The timing of net zero is further discussed in SPM C2.4 and the Cross-Chapter Box 3 in Chapter 3 on net zero CO₂ and net zero GHG emissions.

12 For cases where models do not report all GHGs, missing GHG species are infilled and aggregated into a Kyoto basket of GHG emissions in CO₂-eq defined by the 100 year global warming potential. For each pathway, reporting of CO₂, CH₄, and N₂O emissions was the minimum required for the assessment of the climate

response and the assignment to a climate category. Emissions pathways without climate assessment are not included in the ranges presented here. See Annex III.II.5.

13 Cumulative emissions are calculated from the start of 2020 to the time of net zero and 2100, respectively. They are based on harmonized net CO₂ emissions, ensuring consistency with the WG I assessment of the remaining carbon budget. {Box 3.4, FOOTNOTE 51 in SPM C.2}.

14 Global mean temperature change for category (at peak, if peak temperature occurs before 2100, and in 2100) relative to 1850–1900, based on the median global warming for each pathway assessed using the probabilistic climate model emulators calibrated to the AR6 WG I assessment, see also SPM Scenarios Box. {SPM FOOTNOTE 12, WG I Cross Chapter Box 7.1, Annex III.II.2.5}.

15 Probability of staying below the temperature thresholds for the pathways in each category, taking into consideration the range of uncertainty from the climate model emulators consistent with the AR6 WG I assessment. The probabilities refer to the probability at peak temperature. Note that in the case of temperature overshoot (e.g., category C2 and some pathways in C1), the probabilities of staying below at the end of the century are higher than the probabilities at peak temperature.

<START BOX SPM.1 HERE>

Box SPM.1: Assessment of modelled global emission scenarios

A wide range of modelled global emission pathways and scenarios from the literature is assessed in this report, including pathways and scenarios with and without mitigation.[FOOTNOTE 45] Emissions pathways and scenarios project the evolution of GHG emissions based on a set of internally consistent assumptions about future socio-economic conditions and related mitigation measures.[FOOTNOTE 46] These are quantitative projections and are neither predictions nor forecasts. Around half of all modelled global emission scenarios assume cost-effective approaches that rely on least-cost emission abatement options globally. The other half looks at existing policies and regionally and sectorally differentiated actions. Most do not make explicit assumptions about global equity, environmental justice or intra-regional income distribution. Global emission pathways, including those based on cost effective approaches contain regionally differentiated assumptions and outcomes, and have to be assessed with the careful recognition of these assumptions. This assessment focuses on their global characteristics. The majority of the assessed scenarios (about 80%) have become available since the SR1.5, but some were assessed in that report. Scenarios with and without mitigation were categorised based on their projected global warming over the 21st century, following the same scheme as in the SR1.5 for warming up to and including 2°C. {1.5, 3.2, 3.3, Annex III.II.2, Annex III.II.3}

FOOTNOTE 45: In the literature, the terms pathways and scenarios are used interchangeably, with the former more frequently used in relation to climate goals. For this reason, this SPM uses mostly the term (emissions and mitigation) pathways. {Annex III.II.1.1}

FOOTNOTE 46: Key assumptions relate to technology development in agriculture and energy systems and socio-economic development, including demographic and economic projections. IPCC is neutral with regard to the assumptions underlying the scenarios in the literature assessed in this report, which do not cover all possible futures. Additional scenarios may be developed. The underlying population assumptions range from 8.5 to 9.7 billion in 2050 and 7.4 to 10.9 billion in 2100 (5-95th percentile) starting from 7.6 billion in 2019. The underlying assumptions on global GDP growth (ppp) range from 2.5 to 3.5% per year in the 2019-2050 period and 1.3 to 2.1% per year in the 2050-2100 (5-95th percentile). Many underlying assumptions are regionally differentiated. {1.5; 3.2; 3.3; Figure 3.9; Annex III.II.1.4; Annex III.II.3}

Scenario categories are defined by their likelihood of exceeding global warming levels (at peak and in 2100) and referred to in this report as follows [FOOTNOTE 47, 48]:

- Category C1 comprises modelled scenarios that limit warming to 1.5°C in 2100 with a likelihood of greater than 50%, and reach or exceed warming of 1.5°C during the 21st century with a likelihood of 67% or less. In this report, these scenarios are referred to as scenarios that limit warming to 1.5°C (>50%) with no or limited overshoot. Limited overshoot refers to exceeding 1.5°C global warming by up to about 0.1°C and for up to several decades. [FOOTNOTE 49]
- Category C2 comprises modelled scenarios that limit warming to 1.5°C in 2100 with a likelihood of greater than 50%, and exceed warming of 1.5°C during the 21st century with a likelihood of greater than 67%. In this report, these scenarios are also referred to as scenarios

that return warming to 1.5°C (>50%) after a high overshoot. High overshoot refers to temporarily exceeding 1.5°C global warming by 0.1-0.3°C for up to several decades.

- Category C3 comprises modelled scenarios that limit peak warming to 2°C throughout the 21st century with a likelihood of greater than 67%. In this report, these scenarios are also referred to as scenarios that limit warming to 2°C (>67%).
- Categories C4-C7 comprise modelled scenarios that limit warming to 2°C, 2.5°C, 3°C, 4°C, respectively, throughout the 21st century with a likelihood of greater than 50%. In some scenarios in C4 and many scenarios in C5-C7, warming continues beyond the 21st century.
- Category C8 comprises modelled scenarios that exceed warming of 4°C during the 21st century with a likelihood of 50% or greater. In these scenarios warming continues to rise beyond the 21st century.

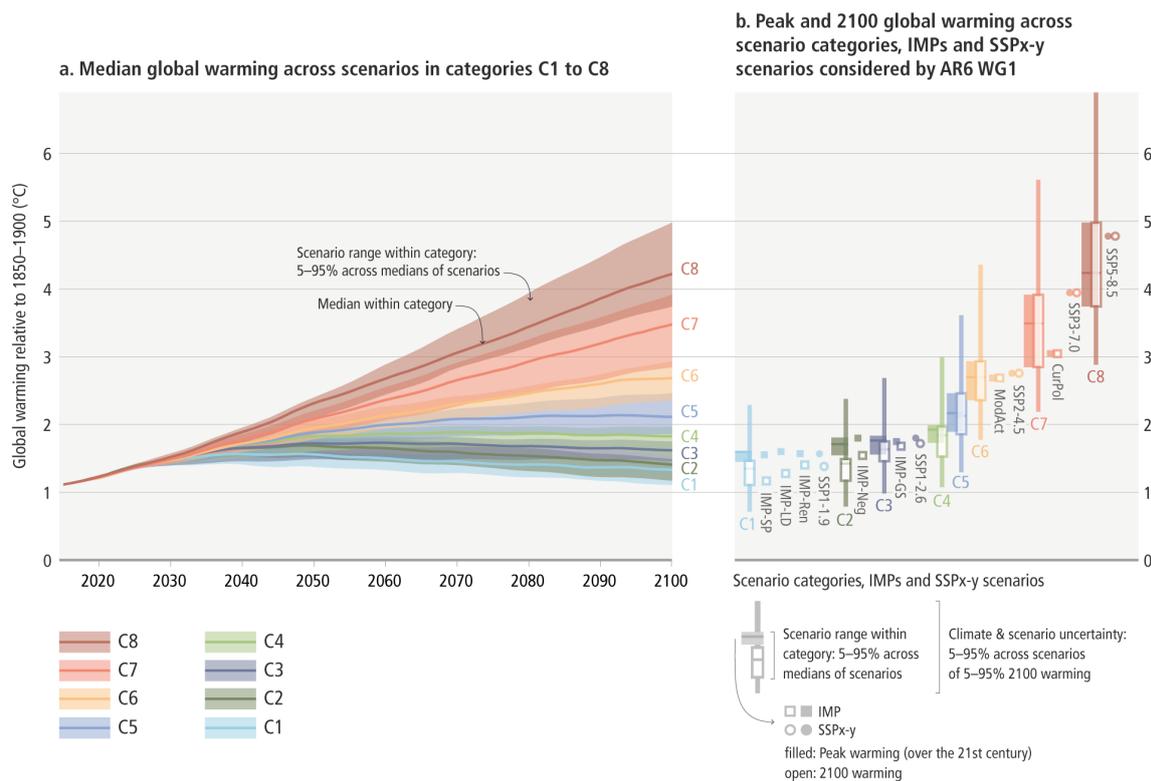
Categories of modelled scenarios are distinct and do not overlap; they do not contain categories consistent with lower levels of global warming, e.g., the category of C3 scenarios that limit warming to 2°C (>67%) does not include the C1 and C2 scenarios that limit or return warming to 1.5°C (>50%). Where relevant, scenarios belonging to the group of categories C1-C3 are referred to in this report as scenarios that limit warming to 2°C (>67%) or lower.

FOOTNOTE 47: The future scenario projections presented here are consistent with the total observed increase in global surface temperature between 1850-1900 and 1995-2014 as well as to 2011-2020 (with best estimates of 0.85 and 1.09°C, respectively) assessed in WGI. The largest contributor to historical human-induced warming is CO₂, with historical cumulative CO₂ emissions from 1850 to 2019 being 2400 ± 240 (GtCO₂). {WGI SPM A.1.2, WGI Table SPM.2, WGI Table 5.1, Section B}

FOOTNOTE 48: In case no explicit likelihood is provided, the reported warming levels are associated with a likelihood of >50%.

FOOTNOTE 49: Scenarios in this category are found to have simultaneous likelihood to limit peak global warming to 2°C throughout the 21st century of close to and more than 90%.

The range of assessed scenarios results in a range of 21st century projected global warming.



Box SPM.1, Figure 1

Projected global mean warming of the ensemble of modelled scenarios included in the climate categories C1–C8 and IMPs (based on emulators calibrated to the WGI assessment), as well as five illustrative scenarios (SSPx-y) as considered by AR6 WG I. The left panel shows the p5–p95 range of projected median warming across global modelled pathways within a category, with the category medians (line). The right panel shows the peak and 2100 emulated temperature outcomes for the categories C1 to C8 and for IMPs, and the five illustrative scenarios (SSPx-y) as considered by AR6 WG I. The boxes show the p5–p95 range within each scenario category as in panel-a. The combined p5–p95 range across scenarios and the climate uncertainty for each category C1– C8 is also shown for 2100 warming (thin vertical lines). {Table SPM.1, Figure 3.11, WGI Figure SPM.8}

Methods to project global warming associated with the scenarios were updated to ensure consistency with the AR6 WG1 assessment of physical climate science [FOOTNOTE 50]: {3.2, Annex III.II.2.5, WG I Cross-chapter box 7.1}

FOOTNOTE 50: This involved improved methodologies to use climate emulators (MAGICC7 and FAIR v1.6), which were evaluated and calibrated to closely match the global warming response to emissions as assessed in AR6 WGI. It included harmonisation of global GHG emissions in 2015 in modelled scenarios (51–56 GtCO₂-eq; 5th to 95th percentiles) with the corresponding emission value underlying the CMIP6 projected climate response assessed by WG I (54 GtCO₂-eq), based on similar data sources of historical emissions that are updated over time. The assessment of past GHG emissions in Chapter 2 of the report is based on a more recent dataset providing emissions of 57 [±6.3] GtCO₂-eq in 2015 (B.1). Differences are well within the assessed uncertainty range, and arise mainly from differences in estimated CO₂-LULUCF emissions, which are subject to large uncertainties, high annual variability and revisions over time. Projected rates of global emission reduction in mitigation scenarios

are reported relative to modelled global emissions in 2019 rather than the global emissions reported in Chapter 2; this ensures internal consistency in assumptions about emission sources and activities, as well as consistency with temperature projections based on the physical climate science assessment by WG I. {Annex III.II.2.5}

These updated methods affect the categorisation of some scenarios. On average across scenarios, peak global warming is projected to be lower by up to about $0.05[\pm 0.1]^{\circ}\text{C}$ than if the same scenarios were evaluated using the SR1.5 methodology, and global warming in 2100 is projected to be lower by about $0.1[\pm 0.1]^{\circ}\text{C}$. {Annex III.II.2.5.1, Annex III, Figure II.3}

Resulting changes to the emission characteristics of scenario categories described in Table SPM.1 interact with changes in the characteristics of the wider range of emission scenarios published since the SR1.5. Proportionally more scenarios assessed in AR6 are designed to limit temperature overshoot and more scenarios limit large-scale net negative CO₂ emissions than in SR1.5. As a result, AR6 scenarios in the lowest temperature category (C1) generally reach net zero GHG emissions later in the 21st century than scenarios in the same category assessed in SR1.5, and about half do not reach net zero GHG by 2100. The rate of decline of GHG emissions in the near term by 2030 in category C1 scenarios is very similar to the assessed rate in SR1.5, but absolute GHG emissions of category C1 scenarios in AR6 are slightly higher in 2030 than in SR1.5, since the reductions start from a higher emissions level in 2020. (Table SPM.1) {Annex III 2.5, 3.2, 3.3}

The large number of global emissions scenarios assessed, including 1202 scenarios with projected global warming outcomes using climate emulators, come from a wide range of modelling approaches. They include the five illustrative scenarios (Shared Socioeconomic Pathways; SSPs) assessed by WG I for their climate outcomes but cover a wider and more varied set in terms of assumptions and modelled outcomes. For this assessment, Illustrative Mitigation Pathways (IMPs) were selected from this larger set to illustrate a range of different mitigation strategies that would be consistent with different warming levels. The IMPs illustrate pathways that achieve deep and rapid emissions reductions through different combinations of mitigation strategies. The IMPs are not intended to be comprehensive and do not address all possible themes in the underlying report. They differ in terms of their focus, for example, placing greater emphasis on renewables (IMP-Ren), deployment of carbon dioxide removal that result in net negative global GHG emissions (IMP-Neg) and efficient resource use as well as shifts in consumption patterns globally, leading to low demand for resources, while ensuring a high level of services and satisfying basic needs (IMP-LD) (Figure SPM.5). Other IMPs illustrate the implications of a less rapid introduction of mitigation measures followed by a subsequent gradual strengthening (IMP-GS), and how shifting global pathways towards sustainable development, including by reducing inequality, can lead to mitigation (IMP-SP). The IMPs reach different climate goals as indicated in Table SPM.1 and Figure Box SPM.1. {1.5, 3.1, 3.2, 3.3, 3.6, Figure 3.7, Figure 3.8, Box 3.4, Annex III.II.2.4}

<END BOX SPM.1 HERE>

C.2 Global net zero CO₂ emissions are reached in the early 2050s in modelled pathways that limit warming to 1.5°C (>50%) with no or limited overshoot, and around the early 2070s in modelled pathways that limit warming to 2°C (>67%). Many of these pathways continue to net negative CO₂ emissions after the point of net zero. These pathways also include deep reductions in other GHG emissions. The level of peak warming depends on cumulative CO₂ emissions until the time of net zero CO₂ and the change in non-CO₂ climate forcings by the time of peaking. Deep

GHG emissions reductions by 2030 and 2040, particularly reductions of methane emissions, lower peak warming, reduce the likelihood of overshooting warming limits and lead to less reliance on net negative CO₂ emissions that reverse warming in the latter half of the century. Reaching and sustaining global net zero GHG emissions results in a gradual decline in warming. (*high confidence*) (Table SPM.1) {3.3, 3.5, Box 3.4, Cross-Chapter Box 3 in Chapter 3, AR6 WG I SPM D1.8}

C.2.1 Modelled global pathways limiting warming to 1.5°C (>50%) with no or limited overshoot are associated with projected cumulative net CO₂ emissions [FOOTNOTE 51] until the time of net zero CO₂ of 510 [330–710] GtCO₂. Pathways limiting warming to 2°C (>67%) are associated with 890 [640–1160] GtCO₂ (Table SPM.1). (*high confidence*). {3.3, Box 3.4}

FOOTNOTE 51: Cumulative net CO₂ emissions from the beginning of the year 2020 until the time of net zero CO₂ in assessed pathways are consistent with the remaining carbon budgets assessed by WG I, taking account of the ranges in the WG III temperature categories and warming from non-CO₂ gases. {Box 3.4}

C.2.2 Modelled global pathways that limit warming to 1.5°C (>50%) with no or limited overshoot involve more rapid and deeper near-term GHG emissions reductions through to 2030, and are projected to have less net negative CO₂ emissions and less carbon dioxide removal (CDR) in the longer term, than pathways that return warming to 1.5°C (>50%) after a high overshoot (C2 category). Modelled pathways that limit warming to 2°C (>67%) have on average lower net negative CO₂ emissions compared to pathways that limit warming to 1.5°C (>50%) with no or limited overshoot and pathways that return warming to 1.5°C (>50%) after a high overshoot (C1 and C2 categories respectively). Modelled pathways that return warming to 1.5°C (>50%) after a high overshoot (C2 category) show near-term GHG emissions reductions similar to pathways that limit warming to 2°C (>67%) (C3 category). For a given peak global warming level, greater and more rapid near-term GHG emissions reductions are associated with later net zero CO₂ dates. (*high confidence*) (Table SPM.1) {3.3, Table 3.5, Cross-Chapter Box 3 in Chapter 3, Annex I: Glossary}

C.2.3 Future non-CO₂ warming depends on reductions in non-CO₂ GHG, aerosol and their precursor, and ozone precursor emissions. In modelled global low emission pathways, the projected reduction of cooling and warming aerosol emissions over time leads to net warming in the near- to mid-term. In these mitigation pathways, the projected reductions of cooling aerosols are mostly due to reduced fossil fuel combustion that was not equipped with effective air pollution controls. Non-CO₂ GHG emissions at the time of net zero CO₂ are projected to be of similar magnitude in modelled pathways that limit warming to 2°C (>67%) or lower. These non-CO₂ GHG emissions are about 8 [5–11] GtCO₂-eq per year, with the largest fraction from CH₄ (60% [55–80%]), followed by N₂O (30% [20–35%]) and F-gases (3% [2–20%]). [FOOTNOTE 52] Due to the short lifetime of CH₄ in the atmosphere, projected deep reduction of CH₄ emissions up until the time of net zero CO₂ in modelled mitigation pathways effectively reduces peak global warming. (*high confidence*) {3.3, AR6 WG I SPM D1.7}

FOOTNOTE 52: All numbers here rounded to the closest 5%, except values below 5% (for F-gases).

C.2.4 At the time of global net zero GHG emissions, net negative CO₂ emissions counterbalance metric-weighted non-CO₂ GHG emissions. Typical emissions pathways that reach and sustain global net zero GHG emissions based on the 100 year global warming potential (GWP100) [FOOTNOTE 7] are projected to result in a gradual decline of global warming. About half of the assessed pathways that limit warming to 1.5°C (>50%) with no or limited overshoot (C1 category) reach net zero GHG emissions during the second half of the 21st century. These pathways show greater reduction in global warming after the peak to 1.2 [1.1–1.4]°C by 2100 than modelled pathways in the same category that

do not reach net zero GHG emissions before 2100 and that result in warming of 1.4 [1.3–1.5]°C by 2100. In modelled pathways that limit warming to 2°C (>67%) (C3 category), there is no significant difference in warming by 2100 between those pathways that reach net zero GHGs (around 30%) and those that do not (*high confidence*). In pathways that limit warming to 2°C (>67%) or lower and that do reach net zero GHG, net zero GHG occurs around 10–40 years later than net zero CO₂ emissions (*medium confidence*). {3.3, Cross-Chapter Box 3 in Chapter 3, Cross-Chapter Box 2 in Chapter 2; AR6 WG I SPM D1.8}

C.3 All global modelled pathways that limit warming to 1.5°C (>50%) with no or limited overshoot, and those that limit warming to 2°C (>67%) involve rapid and deep and in most cases immediate GHG emission reductions in all sectors. Modelled mitigation strategies to achieve these reductions include transitioning from fossil fuels without CCS to very low- or zero-carbon energy sources, such as renewables or fossil fuels with CCS, demand side measures and improving efficiency, reducing non-CO₂ emissions, and deploying carbon dioxide removal (CDR) methods to counterbalance residual GHG emissions. Illustrative Mitigation Pathways (IMPs) show different combinations of sectoral mitigation strategies consistent with a given warming level. (*high confidence*) (Figure SPM.5) {3.2, 3.3, 3.4, 6.4, 6.6}

C.3.1 There is a variation in the contributions of different sectors in modelled mitigation pathways, as illustrated by the Illustrative Mitigation Pathways. However, modelled pathways that limit warming to 2°C (>67%) or lower share common characteristics, including rapid and deep GHG emission reductions. Doing less in one sector needs to be compensated by further reductions in other sectors if warming is to be limited. (*high confidence*) (Figure SPM.5) {3.2, 3.3, 3.4}

C.3.2 In modelled pathways that limit warming to 1.5°C (>50%) with no or limited overshoot, the global use of coal, oil and gas in 2050 is projected to decline with median values of about 95%, 60% and 45% compared to 2019. The interquartile ranges are (80 to 100%), (40 to 75%) and (20 to 60%) and the p5-p95 ranges are [60 to 100%], [25 to 90%] and [-30 to 85%], respectively. In modelled pathways that limit warming to 2°C (>67%), these projected declines have a median value and interquartile range of 85% (65 to 95%), 30% (15 to 50%) and 15% (-10 to 40%) respectively by 2050. The use of coal, oil and gas without CCS in modelled pathways that limit warming to 1.5°C (>50%) with no or limited overshoot is projected to be reduced to a greater degree, with median values of about 100%, 60% and 70% in 2050 compared to 2019. The interquartile ranges are (95 to 100%), (45 to 75%) and (60 to 80%) and the p5-p95 range of about [85 to 100%], [25 to 90%], and [35 to 90%] for coal, oil and gas respectively. In these global modelled pathways, in 2050 almost all electricity is supplied from zero or low-carbon sources, such as renewables or fossil fuels with CCS, combined with increased electrification of energy demand. As indicated by the ranges, choices in one sector can be compensated for by choices in another while being consistent with assessed warming levels. [FOOTNOTE 53] (*high confidence*) {3.4, 3.5, Table 3.6, Figure 3.22, Figure 6.35}

FOOTNOTE 53: Most but not all models include the use of fossil fuels for feedstock with varying underlying standards.

C.3.3 In modelled pathways that reach global net zero CO₂ emissions, at the point they reach net zero, 5-16 GtCO₂ of emissions from some sectors are compensated for by net negative CO₂ emissions in other sectors. In most global modelled pathways that limit warming to 2°C (>67%) or lower, the AFOLU sector, via reforestation and reduced deforestation, and the energy supply sector reach net zero CO₂ emissions earlier than the buildings, industry and transport sectors. (*high confidence*) (Figure SPM.5, panel e and f) {3.4}

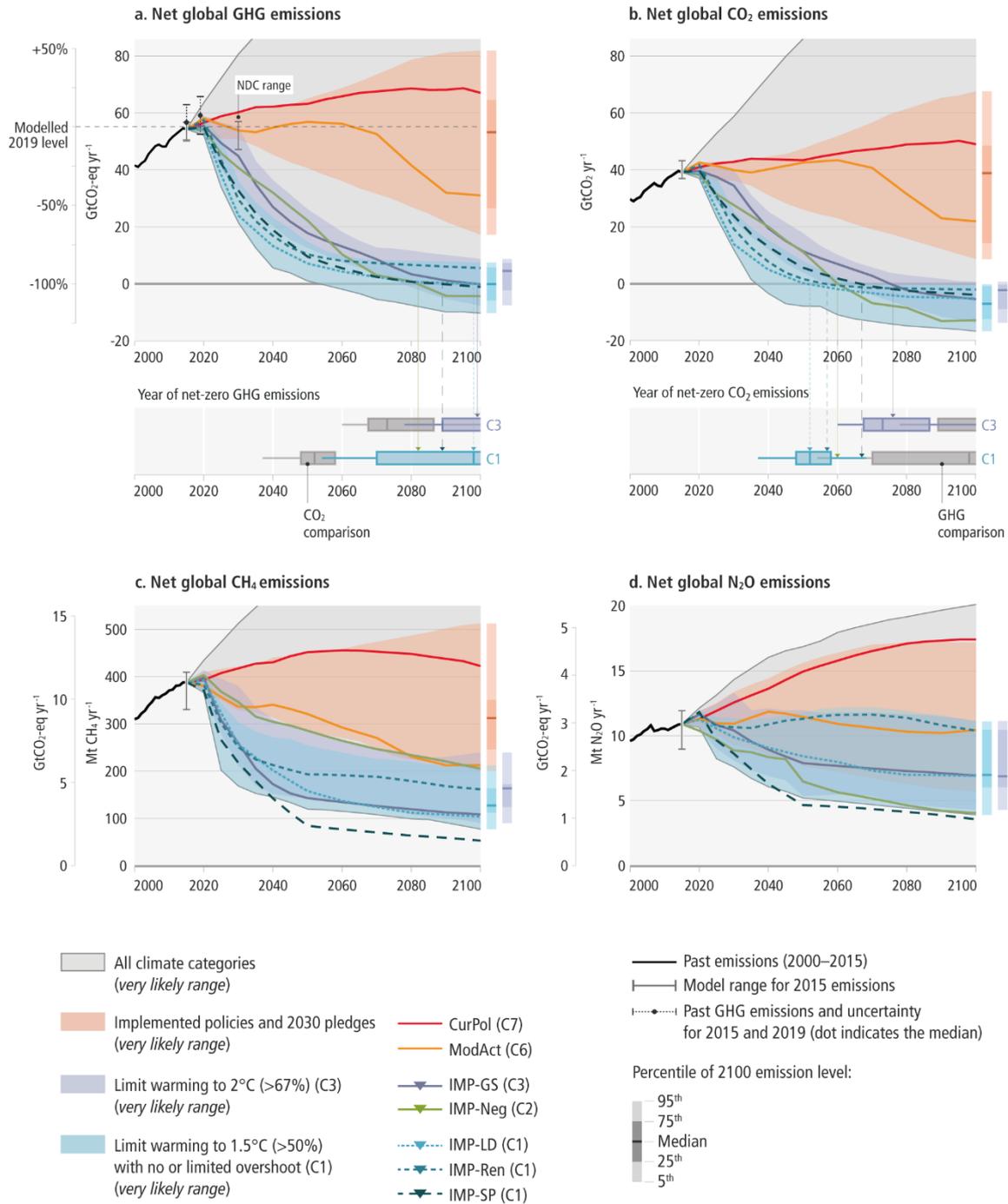
C.3.4 In modelled pathways that reach global net zero GHG emissions, at the point they reach net zero GHG, around 74% [54 to 90%] of global emissions reductions are achieved by CO₂ reductions in energy supply and demand, 13% [4 to 20%] by CO₂ mitigation options in the AFOLU sector, and 13% [10 to 18%] through the reduction of non-CO₂ emissions from land-use, energy and industry (*medium confidence*). (Figure SPM.5f) {3.3, 3.4}

C.3.5 Methods and levels of CDR deployment in global modelled mitigation pathways vary depending on assumptions about costs, availability and constraints. [FOOTNOTE 54] In modelled pathways that report CDR and that limit warming to 1.5°C (>50%) with no or limited overshoot, global cumulative CDR during 2020–2100 from Bioenergy with Carbon Dioxide Capture and Storage (BECCS) and Direct Air Carbon Dioxide Capture and Storage (DACCS) is 30–780 GtCO₂ and 0–310 GtCO₂, respectively. In these modelled pathways, the AFOLU sector contributes 20–400 GtCO₂ net negative emissions. Total cumulative net negative CO₂ emissions including CDR deployment across all options represented in these modelled pathways are 20–660 GtCO₂. In modelled pathways that limit warming to 2°C (>67%), global cumulative CDR during 2020–2100 from BECCS and DACCS is 170–650 and 0–250 GtCO₂ respectively, the AFOLU sector contributes 10–250 GtCO₂ net negative emissions, and total cumulative net negative CO₂ emissions are around 40 [0–290] GtCO₂. (Table SPM.1) (*high confidence*) {Table 3.2, 3.3, 3.4}

FOOTNOTE 54: Aggregate levels of CDR deployment are higher than total net negative CO₂ emissions given that some of the deployed CDR is used to counterbalance remaining gross emissions. Total net negative CO₂ emissions in modelled pathways might not match the aggregated net negative CO₂ emissions attributed to individual CDR methods. Ranges refer to the 5–95th percentile across modelled pathways that include the specific CDR method. Cumulative levels of CDR from AFOLU cannot be quantified precisely given that: a) some pathways assess CDR deployment relative to a baseline; and b) different models use different reporting methodologies that in some cases combine gross emissions and removals in AFOLU. Total CDR from AFOLU equals or exceeds the net negative emissions mentioned.

C.3.6 All mitigation strategies face implementation challenges, including technology risks, scaling, and costs. Many challenges, such as dependence on CDR, pressure on land and biodiversity (e.g., bioenergy) and reliance on technologies with high upfront investments (e.g., nuclear), are significantly reduced in modelled pathways that assume using resources more efficiently (e.g., IMP-LD) or shift global development towards sustainability (e.g., IMP-SP). (*high confidence*) (Figure SPM 5) {3.2, 3.4, 3.7, 3.8, 4.3, 5.1}

Modelled mitigation pathways that limit warming to 1.5°C, and 2°C, involve deep, rapid and sustained emissions reductions.



Net zero CO₂ and net zero GHG emissions are possible through different modelled mitigation pathways.

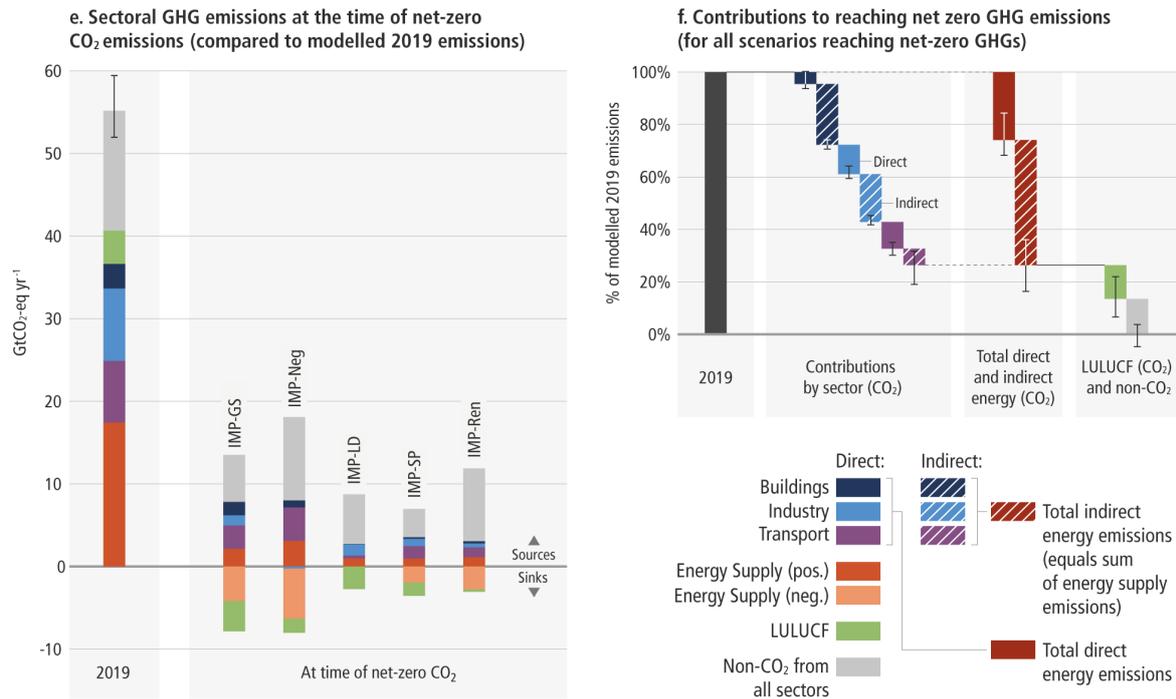


Figure SPM.5: Illustrative Mitigation Emissions Pathways (IMPs) and net zero CO₂ and GHG emissions strategies

Panel a and b show the development of global GHG and CO₂ emissions in modelled global pathways (upper sub-panels) and the associated timing of when GHG and CO₂ emissions reach net zero (lower sub-panels). Panels c and d show the development of global CH₄ and N₂O emissions, respectively. Coloured ranges denote the 5th to 95th percentile across pathways. The red ranges depict emissions pathways assuming policies that were implemented by the end of 2020 and pathways assuming implementation of NDCs (announced prior to COP26). Ranges of modelled pathways that limit warming to 1.5°C (>50%) with no or limited overshoot are shown in light blue (category C1) and pathways that limit warming to 2°C (>67%) are shown in light purple (category C3). The grey range comprises all assessed pathways (C1-C8) from the 5th percentile of the lowest warming category (C1) to the 95th percentile of the highest warming category (C8). The modelled pathway ranges are compared to the emissions from two pathways illustrative of high emissions (CurPol and ModAct) and five Illustrative Mitigation Pathways (IMPs): IMP-LD, IMP-Ren, IMP-SP, IMP-Neg and IMP-GS. Emissions are harmonised to the same 2015 base year. The vertical error bars in 2015 show the 5-95th percentile uncertainty range of the non-harmonised emissions across the pathways, and the uncertainty range, and median value, in emission estimates for 2015 and 2019. The vertical error bars in 2030 (panel a) depict the assessed range of the NDCs, as announced prior to COP26 (see Figure SPM.4, FOOTNOTE 24).

Panel e shows the sectoral contributions of CO₂ and non-CO₂ emissions sources and sinks at the time when net zero CO₂ emissions are reached in the IMPs. Positive and negative emissions for different IMPs are compared to the GHG emissions from the year 2019. Energy supply (neg.) includes BECCS and DACCS. DACCS features in only two of the five IMPs (IMP-REN, IMP-GS) and contributes <1 % and 64%, respectively, to the net negative emissions in Energy Supply (neg.).

Panel f shows the contribution of different sectors and sources to the emissions reductions from a 2019 baseline for reaching net zero GHG emissions. Bars denote the median emissions reductions for all pathways that reach net zero GHG emissions. The whiskers indicate the p5-p95 range. The contributions of the service sectors (transport, buildings, industry) are split into direct (demand-side) as well as indirect (supply-side) CO₂ emissions

reductions. Direct emissions represent demand-side emissions due to the fuel use in the respective demand sector. Indirect emissions represent upstream emissions due to industrial processes and energy conversion, transmission and distribution. In addition, the contributions from the LULUCF sector and reductions from non-CO₂ emissions sources (green and grey bars) are displayed.

{3.3, 3.4}

C.4 Reducing GHG emissions across the full energy sector requires major transitions, including a substantial reduction in overall fossil fuel use, the deployment of low-emission energy sources, switching to alternative energy carriers, and energy efficiency and conservation. The continued installation of unabated fossil fuel [FOOTNOTE 55] infrastructure will ‘lock-in’ GHG emissions. (*high confidence*) {2.7, 6.6, 6.7, 16.4}

C.4.1 Net-zero CO₂ energy systems entail: a substantial reduction in overall fossil fuel use, minimal use of unabated fossil fuels, and use of CCS in the remaining fossil system [FOOTNOTE 55]; electricity systems that emit no net CO₂; widespread electrification of the energy system including end uses; energy carriers such as sustainable biofuels, low-emissions hydrogen, and derivatives in applications less amenable to electrification; energy conservation and efficiency; and greater physical, institutional, and operational integration across the energy system. CDR will be needed to counter-balance residual emissions in the energy sector. The most appropriate strategies depend on national and regional circumstances, including enabling conditions and technology availability. (*high confidence*) {3.4, 6.6, 11.3, 16.4}

FOOTNOTE 55: In this context, ‘unabated fossil fuels’ refers to fossil fuels produced and used without interventions that substantially reduce the amount of GHG emitted throughout the life-cycle; for example, capturing 90% or more from power plants, or 50-80% of fugitive methane emissions from energy supply. {Box 6.5, 11.3}

C.4.2 Unit cost reductions in key technologies, notably wind power, solar power, and storage, have increased the economic attractiveness of low-emission energy sector transitions through 2030. Maintaining emission-intensive systems may, in some regions and sectors, be more expensive than transitioning to low emission systems. Low-emission energy sector transitions will have multiple co-benefits, including improvements in air quality and health. The long-term economic attractiveness of deploying energy system mitigation options depends, *inter alia*, on policy design and implementation, technology availability and performance, institutional capacity, equity, access to finance, and public and political support. (*high confidence*) {Figure SPM3, 3.4, 6.4, 6.6, 6.7, 13.7}

C.4.3 Electricity systems powered predominantly by renewables are becoming increasingly viable. Electricity systems in some countries and regions are already predominantly powered by renewables. It will be more challenging to supply the entire energy system with renewable energy. Even though operational, technological, economic, regulatory, and social challenges remain, a variety of systemic solutions to accommodate large shares of renewables in the energy system have emerged. A broad portfolio of options such as, integrating systems, coupling sectors, energy storage, smart grids, demand-side management, sustainable biofuels, electrolytic hydrogen and derivatives, and others will ultimately be needed to accommodate large shares of renewables in energy systems. (*high confidence*) {Box 6.8, 6.4, 6.6}

C.4.4 Limiting global warming to 2°C or below will leave a substantial amount of fossil fuels unburned and could strand considerable fossil fuel infrastructure (*high confidence*). Depending on its availability, CCS could allow fossil fuels to be used longer, reducing stranded assets (*high confidence*). The combined global discounted value of the unburned fossil fuels and stranded fossil fuel infrastructure

has been projected to be around 1–4 trillion dollars from 2015 to 2050 to limit global warming to approximately 2°C, and it will be higher if global warming is limited to approximately 1.5°C (*medium confidence*). In this context, coal assets are projected to be at risk of being stranded before 2030, while oil and gas assets are projected to be more at risk of being stranded toward mid-century. A low-emission energy sector transition is projected to reduce international trade in fossil fuels. (*high confidence*) {6.7, Figure 6.35}

C.4.5 Global methane emissions from energy supply, primarily fugitive emissions from production and transport of fossil fuels, accounted for about 18% [13%-23%] of global GHG emissions from energy supply, 32% [22%-42%] of global methane emissions, and 6% [4%-8%] of global GHG emissions in 2019 (*high confidence*). About 50–80% of CH₄ emissions from these fossil fuels could be avoided with currently available technologies at less than USD50 tCO₂-eq⁻¹ (*medium confidence*). {6.3, 6.4.2, Box 6.5, 11.3, 2.2.2, Table 2.1, Figure 2.5; Annex1 Glossary}

C.4.6 CCS is an option to reduce emissions from large-scale fossil-based energy and industry sources, provided geological storage is available. When CO₂ is captured directly from the atmosphere (DACCS), or from biomass (BECCS), CCS provides the storage component of these CDR methods. CO₂ capture and subsurface injection is a mature technology for gas processing and enhanced oil recovery. In contrast to the oil and gas sector, CCS is less mature in the power sector, as well as in cement and chemicals production, where it is a critical mitigation option. The technical geological CO₂ storage capacity is estimated to be on the order of 1000 gigatonnes of CO₂, which is more than the CO₂ storage requirements through 2100 to limit global warming to 1.5°C, although the regional availability of geological storage could be a limiting factor. If the geological storage site is appropriately selected and managed, it is estimated that the CO₂ can be permanently isolated from the atmosphere. Implementation of CCS currently faces technological, economic, institutional, ecological-environmental and socio-cultural barriers. Currently, global rates of CCS deployment are far below those in modelled pathways limiting global warming to 1.5°C or 2°C. Enabling conditions such as policy instruments, greater public support and technological innovation could reduce these barriers. (*high confidence*) {2.5, 6.3, 6.4, 6.7, 11.3, 11.4, Cross-Chapter Box 8 in Chapter 12, Figure TS.31, SRCCS Chapter 5}

C.5 Net-zero CO₂ emissions from the industrial sector are challenging but possible. Reducing industry emissions will entail coordinated action throughout value chains to promote all mitigation options, including demand management, energy and materials efficiency, circular material flows, as well as abatement technologies and transformational changes in production processes. Progressing towards net zero GHG emissions from industry will be enabled by the adoption of new production processes using low and zero GHG electricity, hydrogen, fuels, and carbon management. (*high confidence*) {11.2, 11.3, 11.4, Box TS.4}

C.5.1 The use of steel, cement, plastics, and other materials is increasing globally, and in most regions. There are many sustainable options for demand management, materials efficiency, and circular material flows that can contribute to reduced emissions, but how these can be applied will vary across regions and different materials. These options have a potential for being more used in industrial practice and would need more attention from industrial policy. These options, as well as new production technologies, are generally not considered in recent global scenarios nor in national economy-wide scenarios due to relative newness. As a consequence, the mitigation potential in some scenarios is underestimated compared to bottom-up industry-specific models. (*high confidence*) {3.4, 5.3, Figure 5.7, 11.2, Box 11.2, 11.3, 11.4, 11.5.2, 11.6}

C.5.2 For almost all basic materials – primary metals [FOOTNOTE 56], building materials and chemicals – many low- to zero- GHG intensity production processes are at the *pilot to near-commercial* and in some cases *commercial* stage but not yet established industrial practice. Introducing new sustainable basic materials production processes could increase production costs but, given the small fraction of consumer cost based on materials, are expected to translate into minimal cost increases for final consumers. Hydrogen direct reduction for primary steelmaking is *near-commercial* in some regions. Until new chemistries are mastered, deep reduction of cement process emissions will rely on already commercialised cementitious material substitution and the availability of CCS. Reducing emissions from the production and use of chemicals would need to rely on a life cycle approach, including increased plastics recycling, fuel and feedstock switching, and carbon sourced through biogenic sources, and, depending on availability, CCU, direct air CO₂ capture, as well as CCS. Light industry, mining and manufacturing have the potential to be decarbonised through available abatement technologies (e.g., material efficiency, circularity), electrification (e.g., electrothermal heating, heat pumps) and low- or zero- GHG emitting fuels (e.g., hydrogen, ammonia, and bio-based & other synthetic fuels). (*high confidence*) {Table 11.4, Box 11.2, 11.3, 11.4}

FOOTNOTE 56: Primary metals refers to virgin metals produced from ore.

C.5.3 Action to reduce industry sector emissions may change the location of GHG intensive industries and the organisation of value chains. Regions with abundant low GHG energy and feedstocks have the potential to become exporters of hydrogen-based chemicals and materials processed using low-carbon electricity and hydrogen. Such reallocation will have global distributional effects on employment and economic structure. (*medium confidence*) {Box 11.1}

C.5.4 Emissions intensive and highly traded basic materials industries are exposed to international competition, and international cooperation and coordination may be particularly important in enabling change. For sustainable industrial transitions, broad and sequential national and sub-national policy strategies reflecting regional contexts will be required. These may combine policy packages including: transparent GHG accounting and standards; demand management; materials and energy efficiency policies; R&D and niche markets for commercialisation of low emission materials and products; economic and regulatory instruments to drive market uptake; high quality recycling, low-emissions energy and other abatement infrastructure (e.g., for CCS); and socially inclusive phase-out plans of emissions intensive facilities within the context of just transitions. The coverage of mitigation policies

could be expanded nationally and sub-nationally to include all industrial emission sources, and both available and emerging mitigation options. (*high confidence*) {11.6}

C.6 Urban areas can create opportunities to increase resource efficiency and significantly reduce GHG emissions through the systemic transition of infrastructure and urban form through low-emission development pathways towards net-zero emissions. Ambitious mitigation efforts for established, rapidly growing and emerging cities will encompass 1) reducing or changing energy and material consumption, 2) electrification, and 3) enhancing carbon uptake and storage in the urban environment. Cities can achieve net-zero emissions, but only if emissions are reduced within and outside of their administrative boundaries through supply chains, which will have beneficial cascading effects across other sectors. (*very high confidence*) {8.2, 8.3, 8.4, 8.5, 8.6, Figure 8.21, 13.2}

C.6.1 In modelled scenarios, global consumption-based urban CO₂ and CH₄ emissions [FOOTNOTE 15] are projected to rise from 29 GtCO₂-eq in 2020 to 34 GtCO₂-eq in 2050 with moderate mitigation efforts (intermediate GHG emissions, SSP2-4.5), and up to 40 GtCO₂-eq in 2050 with low mitigation efforts (high GHG emissions, SSP 3-7.0). With ambitious and immediate mitigation efforts, including high levels of electrification and improved energy and material efficiency, global consumption-based urban CO₂ and CH₄ emissions could be reduced to 3 GtCO₂-eq in 2050 in the modelled scenario with very low GHG emissions (SSP1-1.9). [FOOTNOTE 57] (*medium confidence*) {8.3}

FOOTNOTE 15: This estimate is based on consumption-based accounting, including both direct emissions from within urban areas, and indirect emissions from outside urban areas related to the production of electricity, goods and services consumed in cities. These estimates include all CO₂ and CH₄ emission categories except for aviation and marine bunker fuels, land-use change, forestry and agriculture. {8.1, Annex I: Glossary}

FOOTNOTE 57: These scenarios have been assessed by WGI to correspond to intermediate, high and very low GHG emissions.

C.6.2 The potential and sequencing of mitigation strategies to reduce GHG emissions will vary depending on a city's land use, spatial form, development level, and state of urbanisation (*high confidence*). Strategies for established cities to achieve large GHG emissions savings include efficiently improving, repurposing or retrofitting the building stock, targeted infilling, and supporting non-motorised (e.g., walking, bicycling) and public transport. Rapidly growing cities can avoid future emissions by co-locating jobs and housing to achieve compact urban form, and by leapfrogging or transitioning to low-emissions technologies. New and emerging cities will have significant infrastructure development needs to achieve high quality of life, which can be met through energy efficient infrastructures and services, and people-centred urban design. (*high confidence*). For cities, three broad mitigation strategies have been found to be effective when implemented concurrently: i) reducing or changing energy and material use towards more sustainable production and consumption; ii) electrification in combination with switching to low-emission energy sources; and iii) enhancing carbon uptake and storage in the urban environment, for example through bio-based building materials, permeable surfaces, green roofs, trees, green spaces, rivers, ponds and lakes [FOOTNOTE 58]. (*very high confidence*) {5.3, Figure 5.7, Table SM5.2, 8.2, 8.4, 8.6, Figure 8.21, 9.4, 9.6, 10.2}

FOOTNOTE 58: These examples are considered to be a subset of nature-based solutions or ecosystem-based approaches.

C.6.3 The implementation of packages of multiple city-scale mitigation strategies can have cascading effects across sectors and reduce GHG emissions both within and outside a city's administrative boundaries. The capacity of cities to develop and implement mitigation strategies varies with the broader regulatory and institutional settings, as well as enabling conditions, including access to financial and technological resources, local governance capacity, engagement of civil society, and municipal budgetary powers. (*very high confidence*). {Figure 5.7, Table SM5.2, 8.4, 8.5, 8.6, 13.2, 13.3, 13.5, 13.7, Cross-Chapter Box 9}

C.6.4 A growing number of cities are setting climate targets, including net-zero GHG targets. Given the regional and global reach of urban consumption patterns and supply chains, the full potential for reducing consumption-based urban emissions to net-zero GHG can be met only when emissions beyond cities' administrative boundaries are also addressed. The effectiveness of these strategies depends on cooperation and coordination with national and sub-national governments, industry, and civil society, and whether cities have adequate capacity to plan and implement mitigation strategies. Cities can play a positive role in reducing emissions across supply chains that extend beyond cities' administrative boundaries, for example through building codes and the choice of construction materials. (*very high confidence*) {8.4, Box 8.4, 8.5, 9.6, 9.9, 13.5, 13.9}

C.7. In modelled global scenarios, existing buildings, if retrofitted, and buildings yet to be built, are projected to approach net zero GHG emissions in 2050 if policy packages, which combine ambitious sufficiency, efficiency, and renewable energy measures, are effectively implemented and barriers to decarbonisation are removed. Low ambitious policies increase the risk of lock-in buildings in carbon for decades while well-designed and effectively implemented mitigation interventions, in both new buildings and existing ones if retrofitted, have significant potential to contribute to achieving SDGs in all regions while adapting buildings to future climate. (*high confidence*) {9.1, 9.3, 9.4, 9.5, 9.6, 9.9}

C.7.1 In 2019, global direct and indirect GHG emissions from buildings and emissions from cement and steel use for building construction and renovation were 12 GtCO₂-eq. These emissions include indirect emissions from offsite generation of electricity and heat, direct emissions produced onsite and emissions from cement and steel used for building construction and renovation. In 2019, global direct and indirect emissions from non-residential buildings increased by about 55% and those from residential buildings increased by about 50% compared to 1990. The latter increase, according to the decomposition analysis, was mainly driven by the increase of the floor area per capita, population growth and the increased use of emission-intensive electricity and heat while efficiency improvements have partly decreased emissions. There are great differences in the contribution of each of these drivers to regional emissions. (*high confidence*) {9.3}

C.7.2 Integrated design approaches to the construction and retrofit of buildings have led to increasing examples of zero energy or zero carbon buildings in several regions. However, the low renovation rates and low ambition of retrofitted buildings have hindered the decrease of emissions. Mitigation interventions at the design stage include buildings typology, form, and multi-functionality to allow for adjusting the size of buildings to the evolving needs of their users and repurposing unused existing buildings to avoid using GHG-intensive materials and additional land. Mitigation interventions include: at the construction phase, low-emission construction materials, highly efficient building envelope and the integration of renewable energy solutions[FOOTNOTE 59]; at the use phase, highly efficient appliances/ equipment, the optimisation of the use of buildings and the supply with low-emission energy

sources; and at the disposal phase, recycling and re-using construction materials. (*high confidence*) {9.4, 9.5, 9.6, 9.7}

FOOTNOTE 59: Integration of renewable energy solutions refers to the integration of solutions such as solar photovoltaics, small wind turbines, solar thermal collectors, and biomass boilers.

C.7.3 By 2050, bottom-up studies show that up to 61% (8.2 GtCO₂) of global building emissions could be mitigated. Sufficiency policies [FOOTNOTE 60] that avoid the demand for energy and materials contribute 10% to this potential, energy efficiency policies contribute 42%, and renewable energy policies 9%. The largest share of the mitigation potential of new buildings is available in developing countries while in developed countries the highest mitigation potential is within the retrofit of existing buildings. The 2020-2030 decade is critical for accelerating the learning of know-how, building the technical and institutional capacity, setting the appropriate governance structures, ensuring the flow of finance, and in developing the skills needed to fully capture the mitigation potential of buildings. (*high confidence*) {9.3, 9.4, 9.5, 9.6, 9.7, 9.9}

FOOTNOTE 60: Sufficiency policies are a set of measures and daily practices that avoid demand for energy, materials, land and water while delivering human wellbeing for all within planetary boundaries.

C.8 Demand-side options and low-GHG emissions technologies can reduce transport sector emissions in developed countries and limit emissions growth in developing countries (*high confidence*). Demand-focused interventions can reduce demand for all transport services and support the shift to more energy efficient transport modes (*medium confidence*). Electric vehicles powered by low emissions electricity offer the largest decarbonisation potential for land-based transport, on a life cycle basis (*high confidence*). Sustainable biofuels can offer additional mitigation benefits in land-based transport in the short and medium term (*medium confidence*). Sustainable biofuels, low emissions hydrogen, and derivatives (including synthetic fuels) can support mitigation of CO₂ emissions from shipping, aviation, and heavy-duty land transport but require production process improvements and cost reductions (*medium confidence*). Many mitigation strategies in the transport sector would have various co-benefits, including air quality improvements, health benefits, equitable access to transportation services, reduced congestion, and reduced material demand (*high confidence*). {10.2, 10.4, 10.5, 10.6, 10.7}

C.8.1 In scenarios that limit warming to 1.5°C (>50%) with no or limited overshoot, global transport-related CO₂ emissions fall by 59% [42–68% interquartile range] by 2050 relative to modelled 2020 emissions, but with regionally differentiated trends (*high confidence*). In global modelled scenarios that limit warming to 2°C (>67%), transport related CO₂ emissions are projected to decrease by 29% [14–44% interquartile range] by 2050 compared to modelled 2020 emissions. In both categories of scenarios, the transport sector *likely* does not reach zero CO₂ emissions by 2100 so negative emissions are *likely* needed to counterbalance residual CO₂ emissions from the sector (*high confidence*). {3.4, 10.7}

C.8.2 Changes in urban form (e.g., density, land use mix, connectivity, and accessibility) in combination with programmes that encourage changes in consumer behaviour (e.g., transport pricing) could reduce transport related greenhouse gas emissions in developed countries and slow growth in emissions in developing countries (*high confidence*). Investments in public inter- and intra-city transport and active transport infrastructure (e.g., bike and pedestrian pathways) can further support the shift to less GHG-intensive transport modes (*high confidence*). Combinations of systemic changes including, teleworking, digitalisation, dematerialisation, supply chain management, and smart and

shared mobility may reduce demand for passenger and freight services across land, air, and sea (*high confidence*). Some of these changes could lead to induced demand for transport and energy services, which may decrease their GHG emissions reduction potential (*medium confidence*). {5.3, 10.2, 10.8}

C.8.3 Electric vehicles powered by low-GHG emissions electricity have large potential to reduce land-based transport GHG emissions, on a life cycle basis (*high confidence*). Costs of electrified vehicles, including automobiles, two and three wheelers, and buses are decreasing and their adoption is accelerating, but they require continued investments in supporting infrastructure to increase scale of deployment (*high confidence*). Advances in battery technologies could facilitate the electrification of heavy-duty trucks and complement conventional electric rail systems (*medium confidence*). There are growing concerns about critical minerals needed for batteries. Material and supply diversification strategies, energy and material efficiency improvements, and circular material flows can reduce the environmental footprint and material supply risks for battery production (*medium confidence*). Sourced sustainably and with low-GHG emissions feedstocks, bio-based fuels, blended or unblended with fossil fuels, can provide mitigation benefits, particularly in the short- and medium-term (*medium confidence*). Low-GHG emissions hydrogen and hydrogen derivatives, including synthetic fuels, can offer mitigation potential in some contexts and land-based transport segments (*medium confidence*). {3.4, 6.3, 10.3, 10.4, 10.7, 10.8, Box 10.6}

C.8.4 While efficiency improvements (e.g., optimised aircraft and vessel designs, mass reduction, and propulsion system improvements) can provide some mitigation potential, additional CO₂ emissions mitigation technologies for aviation and shipping will be required (*high confidence*). For aviation, such technologies include high energy density biofuels (*high confidence*), and low-emission hydrogen and synthetic fuels (*medium confidence*). Alternative fuels for shipping include low-emission hydrogen, ammonia, biofuels, and other synthetic fuels (*medium confidence*). Electrification could play a niche role for aviation and shipping for short trips (*medium confidence*) and can reduce emissions from port and airport operations (*high confidence*). Improvements to national and international governance structures would further enable the decarbonisation of shipping and aviation (*medium confidence*). Such improvements could include, for example, the implementation of stricter efficiency and carbon intensity standards for the sectors (*medium confidence*). {10.3, 10.5, 10.6, 10.7, 10.8, Box 10.5}

C.8.5 Substantial potential for GHG reductions, both direct and indirect, for the transport sector largely depends on power sector decarbonisation, and low emissions feedstocks and production chains (*high confidence*). Integrated transport and energy infrastructure planning and operations can enable sectoral synergies and reduce the environmental, social, and economic impacts of decarbonising the transport and energy sectors (*high confidence*). Technology transfer and financing can support developing countries leapfrogging or transitioning to low emissions transport systems thereby providing multiple co-benefits (*high confidence*). {10.2, 10.3, 10.4, 10.5, 10.6, 10.7, 10.8}

C.9 **AFOLU mitigation options, when sustainably implemented, can deliver large-scale GHG emission reductions and enhanced removals, but cannot fully compensate for delayed action in other sectors. In addition, sustainably sourced agricultural and forest products can be used instead of more GHG intensive products in other sectors. Barriers to implementation and trade-offs may result from the impacts of climate change, competing demands on land, conflicts with food security and livelihoods, the complexity of land ownership and management systems, and cultural aspects. There are many country-specific opportunities to provide co-benefits (such as biodiversity conservation, ecosystem services, and livelihoods) and avoid risks (for example, through adaptation to climate change). (*high confidence*)** {7.4, 7.6, 7.7, 12.5, 12.6}

C.9.1 The projected economic mitigation potential of AFOLU options between 2020 and 2050, at costs below USD100 tCO₂-eq⁻¹, is 8-14 GtCO₂-eq yr⁻¹ [FOOTNOTE 61] (*high confidence*). 30-50% of this potential is available at less than USD20/tCO₂-eq and could be upscaled in the near term across most regions (*high confidence*). The largest share of this economic potential [4.2-7.4 GtCO₂-eq yr⁻¹] comes from the conservation, improved management, and restoration of forests and other ecosystems (coastal wetlands, peatlands, savannas and grasslands), with reduced deforestation in tropical regions having the highest total mitigation. Improved and sustainable crop and livestock management, and carbon sequestration in agriculture, the latter includes soil carbon management in croplands and grasslands, agroforestry and biochar, can contribute 1.8-4.1 GtCO₂-eq yr⁻¹ reduction. Demand-side and material substitution measures, such as shifting to balanced, sustainable healthy diets [FOOTNOTE 62], reducing food loss and waste, and using bio-materials, can contribute 2.1 [1.1-3.6]GtCO₂-eq yr⁻¹ reduction. In addition, demand-side measures together with the sustainable intensification of agriculture can reduce ecosystem conversion and CH₄ and N₂O emissions, and free-up land for reforestation and restoration, and the producing of renewable energy. The improved and expanded use of wood products sourced from sustainably managed forests also has potential through the allocation of harvested wood to longer-lived products, increasing recycling or material substitution. AFOLU mitigation measures cannot compensate for delayed emission reductions in other sectors. Persistent and region-specific barriers continue to hamper the economic and political feasibility of deploying AFOLU mitigation options. Assisting countries to overcome barriers will help to achieve significant mitigation (*medium confidence*). (Figure SPM.6) {7.1, 7.4, 7.5, 7.6}

FOOTNOTE 61: The global top-down estimates and sectoral bottom-up estimates described here do not include the substitution of emissions from fossil fuels and GHG-intensive materials. 8-14 GtCO₂-eq yr⁻¹ represents the mean of the AFOLU economic mitigation potential estimates from top-down estimates (lower bound of range) and global sectoral bottom-up estimates (upper bound of range). The full range from top-down estimates is 4.1-17.3 GtCO₂-eq yr⁻¹ using a “no policy” baseline. The full range from global sectoral studies is 6.7-23.4 GtCO₂-eq yr⁻¹ using a variety of baselines. (*high confidence*)

FOOTNOTE 62: ‘Sustainable healthy diets’ promote all dimensions of individuals’ health and wellbeing; have low environmental pressure and impact; are accessible, affordable, safe and equitable; and are culturally acceptable, as described in FAO and WHO. The related concept of balanced diets refers to diets that feature plant-based foods, such as those based on coarse grains, legumes, fruits and vegetables, nuts and seeds, and animal-sourced food produced in resilient, sustainable and low-GHG emission systems, as described in SRCCCL.

C.9.2 AFOLU carbon sequestration and GHG emission reduction options have both co-benefits and risks in terms of biodiversity and ecosystem conservation, food and water security, wood supply, livelihoods and land tenure and land-use rights of Indigenous Peoples, local communities and small land owners. Many options have co-benefits but those that compete for land and land-based resources can pose risks. The scale of benefit or risk largely depends on the type of activity undertaken, deployment strategy (e.g., scale, method), and context (e.g., soil, biome, climate, food system, land ownership) that vary geographically and over time. Risks can be avoided when AFOLU mitigation is pursued in response to the needs and perspectives of multiple stakeholders to achieve outcomes that maximize co-benefits while limiting trade-offs. (*high confidence*) {7.4, 7.6, 12.3}

C.9.3 Realising the AFOLU potential entails overcoming institutional, economic and policy constraints and managing potential trade-offs (*high confidence*). Land-use decisions are often spread across a wide range of landowners; demand-side measures depend on billions of consumers in diverse contexts. Barriers to the implementation of AFOLU mitigation include insufficient institutional and financial support, uncertainty over long-term additionality and trade-offs, weak governance, insecure land ownership, the low incomes and the lack of access to alternative sources of income, and the risk of reversal. Limited access to technology, data, and know-how is a barrier to implementation. Research and development are key for all measures. For example, measures for the mitigation of agricultural CH₄ and N₂O emissions with emerging technologies show promising results. However the mitigation of agricultural CH₄ and N₂O emissions is still constrained by cost, the diversity and complexity of agricultural systems, and by increasing demands to raise agricultural yields, and increasing demand for livestock products. (*high confidence*) {7.4, 7.6}

C.9.4 Net costs of delivering 5-6 Gt CO₂ yr⁻¹ of forest related carbon sequestration and emission reduction as assessed with sectoral models are estimated to reach to ~USD400 billion yr⁻¹ by 2050. The costs of other AFOLU mitigation measures are highly context specific. Financing needs in AFOLU, and in particular in forestry, include both the direct effects of any changes in activities as well as the opportunity costs associated with land use change. Enhanced monitoring, reporting and verification capacity and the rule of law are crucial for land-based mitigation, in combination with policies also recognising interactions with wider ecosystem services, could enable engagement by a wider array of actors, including private businesses, NGOs, and Indigenous Peoples and local communities. (*medium confidence*) {7.6, 7.7}

C.9.5 Context specific policies and measures have been effective in demonstrating the delivery of AFOLU carbon sequestration and GHG emission reduction options but the above-mentioned constraints hinder large scale implementation (*medium confidence*). Deploying land-based mitigation can draw on lessons from experience with regulations, policies, economic incentives, payments (e.g., for biofuels, control of nutrient pollution, water regulations, conservation and forest carbon, ecosystem services, and rural livelihoods), and from diverse forms of knowledge such as Indigenous knowledge, local knowledge and scientific knowledge. Indigenous Peoples, private forest owners, local farmers and communities manage a significant share of global forests and agricultural land and play a central role in land-based mitigation options. Scaling successful policies and measures relies on governance that emphasises integrated land use planning and management framed by SDGs, with support for implementation. (*high confidence*) {7.4, Box 7.2, 7.6}

C.10 Demand-side mitigation encompasses changes in infrastructure use, end-use technology adoption, and socio-cultural and behavioural change. Demand-side measures and new ways of end-use service provision can reduce global GHG emissions in end use sectors by 40-70% by 2050 compared to baseline scenarios, while some regions and socioeconomic groups require additional energy and resources. Demand side mitigation response options are consistent with improving basic wellbeing for all. (*high confidence*) (Figure SPM.6) {5.3, 5.4, Figure 5.6, Figure 5.14, 8.2, 9.4, 10.2, 11.3, 11.4, 12.4, Figure TS.22}

C.10.1 Infrastructure design and access, and technology access and adoption, including information and communication technologies, influence patterns of demand and ways of providing services, such as mobility, shelter, water, sanitation, and nutrition. Illustrative global low demand scenarios, accounting for regional differences, indicate that more efficient end-use energy conversion can improve services while reducing the need for upstream energy by 45% by 2050 compared to 2020. Demand-side mitigation potential differs between and within regions, and some regions and populations require additional energy, capacity, and resources for human wellbeing. The lowest population quartile by

income worldwide faces shortfalls in shelter, mobility, and nutrition. (*high confidence*) {5.2, 5.3, 5.4, 5.5, Figure 5.6, Figure 5.10, Figure TS.20, Figure TS.22, Table 5.2}

C.10.2 By 2050, comprehensive demand-side strategies across all sectors could reduce CO₂ and non-CO₂ GHG emissions globally by 40–70% compared to the 2050 emissions projection of two scenarios consistent with policies announced by national governments until 2020. With policy support, socio-cultural options, and behavioural change can reduce global GHG emissions of end-use sectors by at least 5% rapidly, with most of the potential in developed countries, and more until 2050, if combined with improved infrastructure design and access. Individuals with high socio-economic status contribute disproportionately to emissions and have the highest potential for emissions reductions, e.g., as citizens, investors, consumers, role models, and professionals. (*high confidence*) (Figure SPM.6){5.2, 5.3, 5.4, 5.5, 5.6, Table SM5.2, 8.4, 9.9, 13.2, 13.5, 13.8, Figure TS.20}

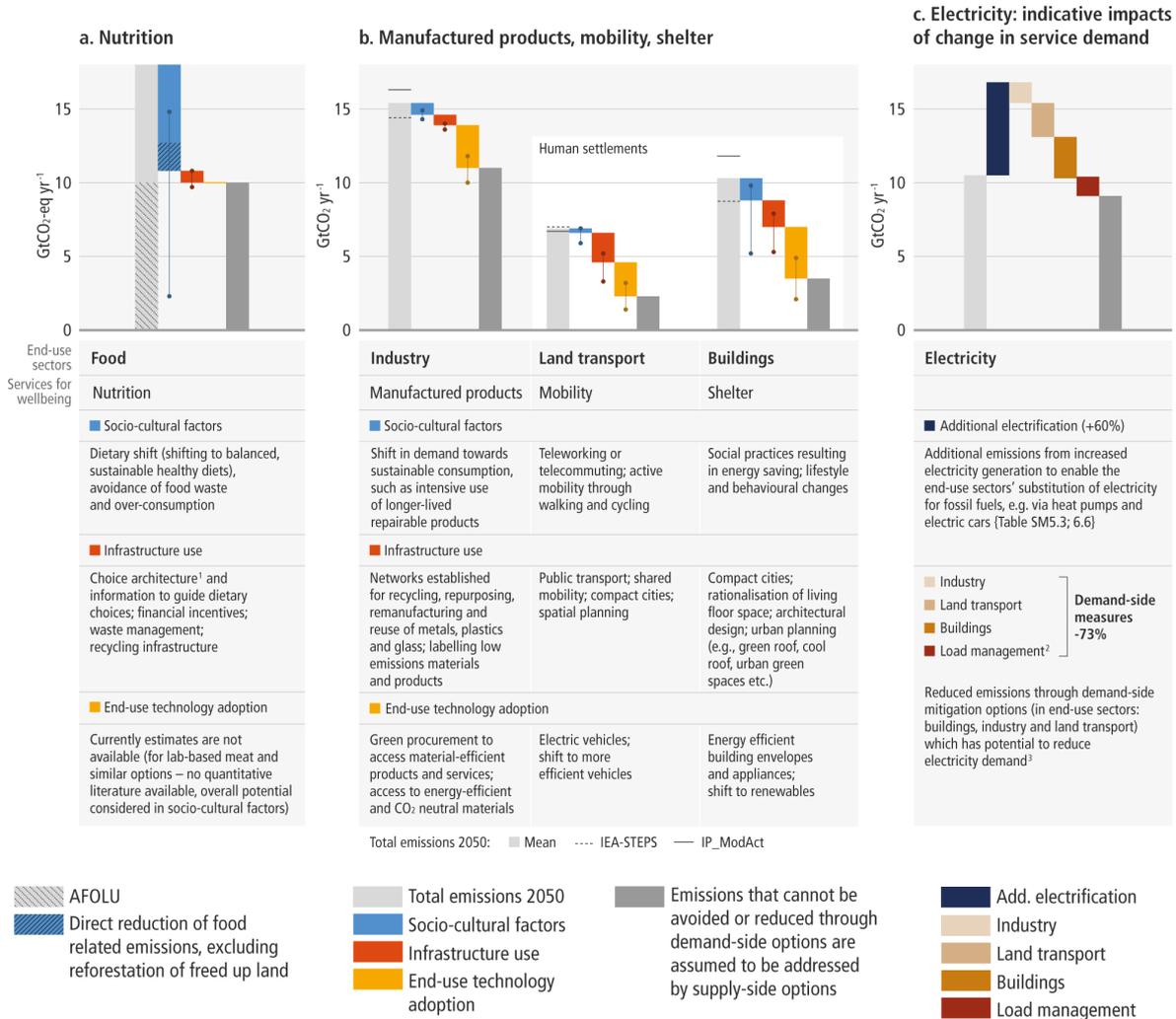
C.10.3 A range of 5-30% of global annual GHG emissions from end-use sectors are avoidable by 2050, compared to 2050 emissions projection of two scenarios consistent with policies announced by national governments until 2020, through changes in the built environment, new and repurposed infrastructures and service provision through compact cities, co-location of jobs and housing, more efficient use of floor space and energy in buildings, and reallocation of street space for active mobility (*high confidence*). (Figure SPM.6) {5.3.1, 5.3.3, 5.4, Figure 5.7, Figure 5.13, Table 5.1, Table 5.5, Table SM5.2, 8.4, 9.5, 10.2, 11.3, 11.4, Table 11.6, Box TS.12}

C.10.4 Choice architecture [FOOTNOTE 63] can help end-users adopt, as relevant to consumers, culture and country contexts, low GHG intensive options such as balanced, sustainable healthy diets[FOOTNOTE 62] acknowledging nutritional needs; food waste reduction; adaptive heating and cooling choices for thermal comfort; integrated building renewable energy; and electric light-duty vehicles, and shifts to walking, cycling, shared pooled and public transit; sustainable consumption by intensive use of longer-lived repairable products (*high confidence*). Addressing inequality and many forms of status consumption [FOOTNOTE 64] and focusing on wellbeing supports climate change mitigation efforts (*high confidence*). (Figure SPM.6) {2.4.3, 2.6.2, 4.2.5, 5.1, 5.2, 5.3, 5.4, Figure 5.4, Figure 5.10, Table 5.2, Table SM5.2, 7.4.5, 8.2, 8.4, 9.4, 10.2, 12.4, Figure TS.20}

FOOTNOTE 63: Choice architecture describes the presentation of choices to consumers, and the impact that presentation has on consumer decision-making.

FOOTNOTE 64: Status consumption refers to the consumption of goods and services which publicly demonstrates social prestige.

Demand-side mitigation can be achieved through changes in socio-cultural factors, infrastructure design and use, and end-use technology adoption by 2050.



¹ The presentation of choices to consumers, and the impact of that presentation on consumer decision-making.
² Load management refers to demand-side flexibility that cuts across all sectors and can be achieved through incentive design like time of use pricing/monitoring by artificial intelligence, diversification of storage facilities, etc.
³ The impact of demand-side mitigation on electricity sector emissions depends on the baseline carbon intensity of electricity supply, which is scenario dependent.

Figure SPM.6 Indicative potential of demand-side mitigation options by 2050

Figure SPM.6 covers the indicative potential of demand-side options for the year 2050. Figure SPM.7 covers cost and potentials for the year 2030. Demand-side mitigation response options are categorised into three broad domains: ‘socio-cultural factors’, associated with individual choices, behaviour; and lifestyle changes, social norms and culture; ‘infrastructure use’, related to the design and use of supporting hard and soft infrastructure that enables changes in individual choices and behaviour; and ‘end-use technology adoption’, refers to the uptake of technologies by end-users. Demand side mitigation is a central element of the IMP-LD and IMP-SP scenarios (Figure SPM.5).

Panel (a) (Nutrition) demand-side potentials in 2050 assessment is based on bottom-up studies and estimated following the 2050 baseline for the food sector presented in peer-reviewed literature (more information in Supplementary Material 5.II, and 7.4.5). Panel (b) (Manufactured products, mobility, shelter) assessment of potentials for total emissions in 2050 are estimated based on approximately 500 bottom up studies representing all global regions (detailed list is in Table SM5.2). Baseline is provided by the sectoral mean GHG emissions in 2050 of the two scenarios consistent with policies announced by national governments until 2020. The heights of the coloured columns represent the potentials represented by the median value. These are based on a range of values available in the case studies from literature shown in Chapter 5 Supplementary Material II. The range is

shown by the dots connected by dotted lines representing the highest and the lowest potentials reported in the literature.

Panel (a) shows the demand side potential of socio-cultural factors and infrastructure use. The median value of direct emissions (mostly non-CO₂) reduction through socio-cultural factors is 1.9 GtCO₂-eq without considering land-use change through reforestation of freed up land. If changes in land use pattern enabled by this change in food demand are considered, the indicative potential could reach 7 GtCO₂-eq. Panel (b) illustrates mitigation potential in industry, land transport and buildings end-use sectors through demand-side options. Key options are presented in the summary table below the figure and the details are in Table SM5.2.

Panel (c) visualizes how sectoral demand-side mitigation options (presented in Panel (b)) change demand on the electricity distribution system. Electricity accounts for an increasing proportion of final energy demand in 2050 (additional electricity bar) in line with multiple bottom-up studies (detailed list is in Table SM5.3), and Chapters 6 (6.6). These studies are used to compute the impact of end-use electrification which increases overall electricity demand. Some of the projected increase in electricity demand can be avoided through demand-side mitigation options in the domains of socio-cultural factors and infrastructure use in end-use electricity use in buildings, industry, and land transport found in literature based on bottom-up assessments. Dark grey columns show the emissions that cannot be avoided through demand-side mitigation options. {5.3, Figure 5.7, Supplementary Material 5.II}

C.11 The deployment of CDR to counterbalance hard-to-abate residual emissions is unavoidable if net zero CO₂ or GHG emissions are to be achieved. The scale and timing of deployment will depend on the trajectories of gross emission reductions in different sectors. Upscaling the deployment of CDR depends on developing effective approaches to address feasibility and sustainability constraints especially at large scales. (*high confidence*) {3.4, 7.4, 12.3, Cross-Chapter Box 8 in Chapter 12}

C.11.1 CDR refers to anthropogenic activities that remove CO₂ from the atmosphere and store it durably in geological, terrestrial, or ocean reservoirs, or in products. CDR methods vary in terms of their maturity, removal process, timescale of carbon storage, storage medium, mitigation potential, cost, co-benefits, impacts and risks, and governance requirements (*high confidence*). Specifically, maturity ranges from lower maturity (e.g., ocean alkalisation) to higher maturity (e.g., reforestation); removal and storage potential ranges from lower potential (<1 Gt CO₂ yr⁻¹, e.g., blue carbon management) to higher potential (>3 Gt CO₂ yr⁻¹, e.g., agroforestry); costs range from lower cost (e.g., 45-100 USD/tCO₂ for soil carbon sequestration) to higher cost (e.g., 100-300 USD/tCO₂ for DACCS) (*medium confidence*). Estimated storage timescales vary from decades to centuries for methods that store carbon in vegetation and through soil carbon management, to ten thousand years or more for methods that store carbon in geological formations (*high confidence*). The processes by which CO₂ is removed from the atmosphere are categorised as biological, geochemical or chemical. Afforestation, reforestation, improved forest management, agroforestry and soil carbon sequestration are currently the only widely practiced CDR methods (*high confidence*). {7.4, 7.6, 12.3, Table 12.6, Table TS.7, Cross-Chapter Box 8 in Chapter 12, WG I 5.6}

C.11.2 The impacts, risks and co-benefits of CDR deployment for ecosystems, biodiversity and people will be highly variable depending on the method, site-specific context, implementation and scale (*high confidence*). Reforestation, improved forest management, soil carbon sequestration, peatland restoration and blue carbon management are examples of methods that can enhance biodiversity and ecosystem functions, employment and local livelihoods, depending on context (*high confidence*). In contrast, afforestation or production of biomass crops for BECCS or biochar, when poorly implemented, can have adverse socio-economic and environmental impacts, including on biodiversity, food and water security, local livelihoods and on the rights of Indigenous Peoples, especially if implemented at large scales and where land tenure is insecure (*high confidence*). Ocean fertilisation, if implemented, could

lead to nutrient redistribution, restructuring of ecosystems, enhanced oxygen consumption and acidification in deeper waters (*medium confidence*). {7.4, 7.6, 12.3, 12.5}

C.11.3 The removal and storage of CO₂ through vegetation and soil management can be reversed by human or natural disturbances; it is also prone to climate change impacts. In comparison, CO₂ stored in geological and ocean reservoirs (via BECCS, DACCS, ocean alkalisation) and as carbon in biochar is less prone to reversal. (*high confidence*) {6.4, 7.4, 12.3}

C11.4 In addition to deep, rapid, and sustained emission reductions CDR can fulfil three different complementary roles globally or at country level: lowering net CO₂ or net GHG emissions in the near-term; counterbalancing ‘hard-to-abate’ residual emissions (e.g., emissions from agriculture, aviation, shipping, industrial processes) in order to help reach net zero CO₂ or net zero GHG emissions in the mid-term; achieving net negative CO₂ or GHG emissions in the long-term if deployed at levels exceeding annual residual emissions (*high confidence*) {3.3, 7.4, 11.3, 12.3, Cross-Chapter Box 8 in Chapter 12}

C.11.5 Rapid emission reductions in all sectors interact with future scale of deployment of CDR methods, and their associated risks, impacts and co-benefits. Upscaling the deployment of CDR methods depends on developing effective approaches to address sustainability and feasibility constraints, potential impacts, co-benefits and risks. Enablers of CDR include accelerated research, development and demonstration, improved tools for risk assessment and management, targeted incentives and development of agreed methods for measurement, reporting and verification of carbon flows. (*high confidence*) {3.4, 7.6, 12.3}

C.12 Mitigation options costing USD100 tCO₂-eq⁻¹ or less could reduce global GHG emissions by at least half the 2019 level by 2030 (*high confidence*). Global GDP continues to grow in modelled pathways [FOOTNOTE 65] but, without accounting for the economic benefits of mitigation action from avoided damages from climate change nor from reduced adaptation costs, it is a few percent lower in 2050 compared to pathways without mitigation beyond current policies. The global economic benefit of limiting warming to 2°C is reported to exceed the cost of mitigation in most of the assessed literature. (*medium confidence*) (Figure SPM.7) {3.6, 3.8, Cross-Working Group Box 1 in Chapter 3, 12.2, Box TS.7}

FOOTNOTE 65: In modelled pathways that limit warming to 2°C (>67%) or lower.

C.12.1 Based on a detailed sectoral assessment of mitigation options, it is estimated that mitigation options costing USD100 tCO₂-eq⁻¹ or less could reduce global GHG emissions by at least half of the 2019 level by 2030 (options costing less than USD20 tCO₂-eq⁻¹ are estimated to make up more than half of this potential) [FOOTNOTE 66]. For a smaller part of the potential, deployment leads to net cost savings. Large contributions with costs less than USD20 tCO₂-eq⁻¹ come from solar and wind energy, energy efficiency improvements, reduced conversion of natural ecosystems, and CH₄ emissions reductions (coal mining, oil and gas, waste). The mitigation potentials and mitigation costs of individual technologies in a specific context or region may differ greatly from the provided estimates. The assessment of the underlying literature suggests that the relative contribution of the various options could change beyond 2030. (*medium confidence*) (Figure SPM.7) {12.2}

FOOTNOTE 66. The methodology underlying the assessment is described in the caption to Figure SPM.7.

C.12.2 The aggregate effects of climate change mitigation on global GDP are small compared to global projected GDP growth in assessed modelled global scenarios that quantify the macroeconomic implications of climate change mitigation, but that do not account for damages from climate change nor adaptation costs (*high confidence*). For example, compared to pathways that assume the continuation of policies implemented by the end of 2020, assessed global GDP reached in 2050 is reduced by 1.3–2.7% in modelled pathways assuming coordinated global action starting between now and 2025 at the latest to limit warming to 2°C (>67%). The corresponding average reduction in annual global GDP growth over 2020-2050 is 0.04–0.09 percentage points. In assessed modelled pathways, regardless of the level of mitigation action, global GDP is projected to at least double (increase by at least 100%) over 2020-2050. For modelled global pathways in other temperature categories, the reductions in global GDP in 2050 compared to pathways that assume the continuation of policies implemented by the end of 2020 are as follows: 2.6 - 4.2% (C1), 1.6 - 2.8% (C2), 0.8 - 2.1% (C4), 0.5 - 1.2% (C5). The corresponding reductions in average annual global GDP growth over 2020-2050, in percentage points, are as follows: 0.09 - 0.14 (C1), 0.05 - 0.09 (C2), 0.03 - 0.07 (C4), 0.02 - 0.04 (C5) [FOOTNOTE 67]. There are large variations in the modelled effects of mitigation on GDP across regions, depending notably on economic structure, regional emissions reductions, policy design and level of international cooperation [FOOTNOTE 68] (*high confidence*). Country level studies also show large variations in the effect of mitigation on GDP depending notably on the level of mitigation and on the way it is achieved (*high confidence*). Macroeconomic implications of mitigation co-benefits and trade-offs are not quantified comprehensively across the above scenarios and depend strongly on mitigation strategies (*high confidence*). {3.6, 4.2, Box TS.7, Annex III I.2, I.9, I.10 and II.3}

FOOTNOTE 67: These estimates are based on 311 pathways that report effects of mitigation on GDP and that could be classified in temperature categories, but that do not account for damages from climate change nor adaptation costs and that mostly do not reflect the economic impacts of mitigation co-benefits and trade-offs. The ranges given are interquartile ranges. The macroeconomic implications quantified vary largely depending on technology assumptions, climate/emissions target formulation, model structure and assumptions, and the extent to which pre-existing inefficiencies are considered. Models that produced the pathways classified in temperature categories do not represent the full diversity of existing modelling paradigms, and there are in the literature models that find higher mitigation costs, or conversely lower mitigation costs and even gains. {1.7, 3.2, 3.6, Annex III I.2 I.9 I.10 and II.3}

FOOTNOTE 68: In modelled cost-effective pathways with a globally uniform carbon price, without international financial transfers or complementary policies, carbon intensive and energy exporting countries are projected to bear relatively higher mitigation costs because of a deeper transformation of their economies and changes in international energy markets. {3.6}

C.12.3 Estimates of aggregate economic benefits from avoiding damages from climate change, and from reduced adaptation costs, increase with the stringency of mitigation (*high confidence*). Models that incorporate the economic damages from climate change find that the global cost of limiting warming to 2°C over the 21st century is lower than the global economic benefits of reducing warming, unless: i) climate damages are towards the low end of the range; or, ii) future damages are discounted at high rates (*medium confidence*) [FOOTNOTE 69]. Modelled pathways with a peak in global emissions between now and 2025 at the latest, compared to modelled pathways with a later peak in global emissions, entail more rapid near-term transitions and higher up-front investments, but bring long-term gains for the economy, as well as earlier benefits of avoided climate change impacts (*high confidence*). The precise magnitude of these gains and benefits is difficult to quantify. {1.7, 3.6, Cross-Working Group Box 1 in Chapter 3 Box TS.7, WGII SPM B.4}

FOOTNOTE 69: The evidence is too limited to make a similar robust conclusion for limiting warming to 1.5°C.

Many options available now in all sectors are estimated to offer substantial potential to reduce net emissions by 2030. Relative potentials and costs will vary across countries and in the longer term compared to 2030.

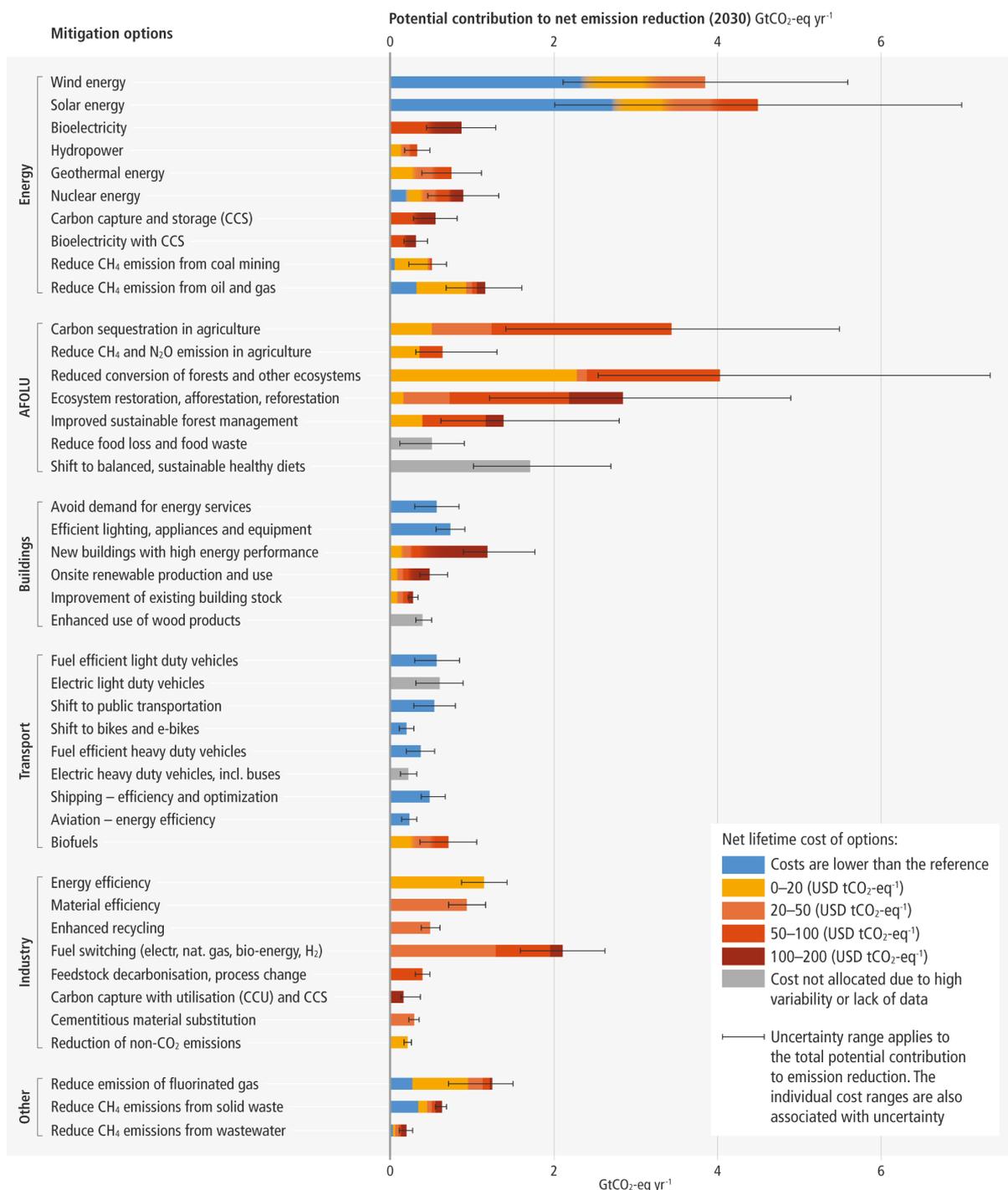


Figure SPM.7: Overview of mitigation options and their estimated ranges of costs and potentials in 2030.

Costs shown are net lifetime costs of avoided greenhouse gas emissions. Costs are calculated relative to a reference technology. The assessments per sector were carried out using a common methodology, including definition of potentials, target year, reference scenarios, and cost definitions. The mitigation potential (shown in the horizontal axis) is the quantity of net greenhouse gas emission reductions that can be achieved by a given mitigation option relative to a specified emission baseline. Net greenhouse gas emission reductions are the sum of reduced emissions and/or enhanced sinks. The baseline used consists of current policy (~ 2019) reference scenarios from the AR6 scenarios database (25/75 percentile values). The assessment relies on approximately 175 underlying sources, that together give a fair representation of emission reduction potentials across all regions. The mitigation potentials are assessed independently for each option and are not necessarily additive. {12.2.1, 12.2.2}

The length of the solid bars represents the mitigation potential of an option. The error bars display the full ranges of the estimates for the total mitigation potentials. Sources of uncertainty for the cost estimates include assumptions on the rate of technological advancement, regional differences, and economies of scale, among others. Those uncertainties are not displayed in the figure.

Potentials are broken down into cost categories, indicated by different colours (see legend). Only discounted lifetime monetary costs are considered. Where a gradual colour transition is shown, the breakdown of the potential into cost categories is not well known or depends heavily on factors such as geographical location, resource availability, and regional circumstances, and the colours indicate the range of estimates. Costs were taken directly from the underlying studies (mostly in the period 2015-2020) or recent datasets. No correction for inflation was applied, given the wide cost ranges used. The cost of the reference technologies were also taken from the underlying studies and recent datasets. Cost reductions through technological learning are taken into account (FOOTNOTE 70).

When interpreting this figure, the following should be taken into account:

- The mitigation potential is uncertain, as it will depend on the reference technology (and emissions) being displaced, the rate of new technology adoption, and several other factors.
- Cost and mitigation potential estimates were extrapolated from available sectoral studies. Actual costs and potentials would vary by place, context and time.
- Beyond 2030, the relative importance of the assessed mitigation options is expected to change, in particular while pursuing long-term mitigation goals, recognising also that the emphasis for particular options will vary across regions (for specific mitigation options see sections C4.1, C5.2, C7.3, C8.3 and C9.1).
- Different options have different feasibilities beyond the cost aspects, which are not reflected in the figure (cf. section E.1).
- The potentials in the cost range 100 to 200 USD tCO₂-eq⁻¹ may be underestimated for some options.
- Costs for accommodating the integration of variable renewable energy sources in electricity systems are expected to be modest until 2030, and are not included because of complexities in attributing such costs to individual technology options.
- Cost range categories are ordered from low to high. This order does not imply any sequence of implementation.
- Externalities are not taken into account.

{12.2, Table 12.3, 6.4, Table 7.3, Supplementary Material Table 9.2, Supplementary Material Table 9.3, 10.6, 11.4, Fig 11.13, Supplementary Material 12.A.2.3}

FOOTNOTE 70: For nuclear energy, modelled costs for long-term storage of radio-active waste are included.

D. Linkages between mitigation, adaptation, and sustainable development

D.1 Accelerated and equitable climate action in mitigating, and adapting to, climate change impacts is critical to sustainable development. Climate change actions can also result in some trade-offs. The trade-offs of individual options could be managed through policy design. The Sustainable Development Goals (SDGs) adopted under the UN 2030 Agenda for Sustainable Development can be used as a basis for evaluating climate action in the context of sustainable development. (*high confidence*) (Figure SPM.8) {1.6, 3.7, 17.3, Figure TS.29}

D.1.1 Human-induced climate change is a consequence of more than a century of net GHG emissions from unsustainable energy use, land-use and land use change, lifestyle and patterns of consumption and production. Without urgent, effective and equitable mitigation actions, climate change increasingly threatens the health and livelihoods of people around the globe, ecosystem health and biodiversity. There are both synergies and trade-offs between climate action and the pursuit of other SDGs. Accelerated and equitable climate action in mitigating, and adapting to, climate change impacts is critical to sustainable development. (*high confidence*) {1.6, Cross-Chapter Box 5 in Chapter 4, 7.2, 7.3, 17.3, WGI, WGII}

D.1.2 Synergies and trade-offs depend on the development context including inequalities, with consideration of climate justice. They also depend on means of implementation, intra- and inter-sectoral interactions, cooperation between countries and regions, the sequencing, timing and stringency of mitigation actions, governance, and policy design. Maximising synergies and avoiding trade-offs pose particular challenges for developing countries, vulnerable populations, and Indigenous Peoples with limited institutional, technological and financial capacity, and with constrained social, human, and economic capital. Trade-offs can be evaluated and minimized by giving emphasis to capacity building, finance, governance, technology transfer, investments, and development and social equity considerations with meaningful participation of Indigenous Peoples and vulnerable populations. (*high confidence*) {1.6, 1.7, 3.7, 5.2, 5.6, 7.4, 7.6, 17.4}

D.1.3 There are potential synergies between sustainable development and energy efficiency and renewable energy, urban planning with more green spaces, reduced air pollution, and demand side mitigation including shifts to balanced, sustainable healthy diets (*high confidence*). Electrification combined with low GHG energy, and shifts to public transport can enhance health, employment, and can elicit energy security and deliver equity (*high confidence*). In industry, electrification and circular material flows contribute to reduced environmental pressures and increased economic activity and employment. However, some industrial options could impose high costs (*medium confidence*). (Figure SPM.8) {5.2, 8.2, 11.3, 11.5, 17.3, Figure TS.29}

D.1.4 Land-based options such as reforestation and forest conservation, avoided deforestation and restoration and conservation of natural ecosystems and biodiversity, improved sustainable forest management, agroforestry, soil carbon management and options that reduce CH₄ and N₂O emissions in agriculture from livestock and soil, can have multiple synergies with the SDGs. These include enhancing sustainable agricultural productivity and resilience, food security, providing additional biomass for human use, and addressing land degradation. Maximising synergies and managing trade-offs depend on specific practices, scale of implementation, governance, capacity building, integration with existing land-use, and the involvement of local communities and Indigenous Peoples and through benefit sharing supported by frameworks such as Land Degradation Neutrality within the UNCCD. (*high confidence*) {3.7, 7.4, 12.5, 17.3}

D.1.5 Trade-offs in terms of employment, water use, land use competition and biodiversity, as well as access to, and the affordability of, energy, food, and water can be avoided by well-implemented land-based mitigation options, especially those that do not threaten existing sustainable land uses and land rights, though more frameworks for integrated policy implementation are required. The sustainability of bioenergy and other biobased products is influenced by feedstock, land management practice, climatic region, the context of existing land management, and the timing, scale and speed of deployment. (*medium confidence*) {3.5, 3.7, 7.4, 12.4, 12.5, 17.1}

D.1.6 CDR methods such as soil carbon sequestration and biochar [FOOTNOTE 71] can improve soil quality and food production capacity. Ecosystem restoration and reforestation sequester carbon in plants and soil, and can enhance biodiversity and provide additional biomass, but can displace food production and livelihoods, which calls for integrated approaches to land use planning, to meet multiple objectives including food security. However, due to limited application of some of the options today, there are some uncertainties about potential benefits (*high confidence*) {3.7, 7.4, 7.6, 12.5, 17.3, Table TS.7}

FOOTNOTE 71: Potential risks, knowledge gaps due to the relative immaturity of use of biochar as soil amendment and unknown impacts of widespread application, and co-benefits of biochar are reviewed in 7.4.3.2.

Mitigation options have synergies with many Sustainable Development Goals, but some options can also have trade-offs. The synergies and trade-offs vary dependent on context and scale.

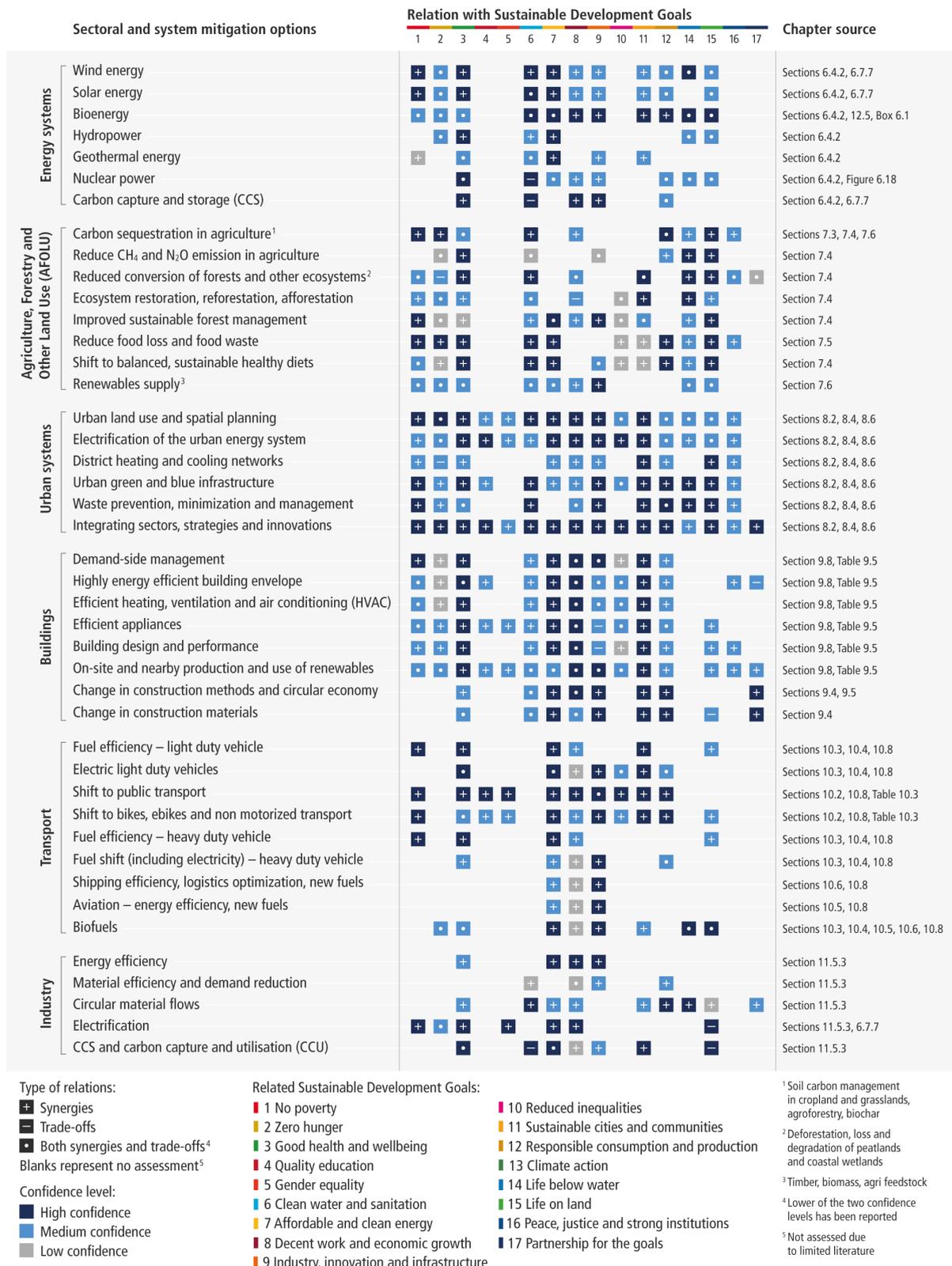


Figure SPM.8 Synergies and trade-offs between sectoral and system mitigation options and the SDGs

The sectoral chapters (Chapters 6–11) include qualitative assessments of synergies and trade-offs between sectoral mitigation options and the SDGs. Figure SPM.8 presents a summary of the chapter-level assessment for selected mitigation options (see Supplementary Material Table 17.1 for the underlying assessment). The last column provides a line of sight to the sectoral chapters, which provide details on context specificity and dependence of interactions on the scale of implementation. Blank cells indicate that interactions have not been assessed due to limited literature. They do not indicate the absence of interactions between mitigation options and the SDGs. Confidence levels depend on the quality of evidence and level of agreement in the underlying literature assessed by the sectoral chapters. Where both synergies and trade-offs exist, the lower of the confidence levels for these interactions is used.

Some mitigation options may have applications in more than one sector or system. The interactions between mitigation options and the SDGs might differ depending on the sector or system, and also on the context and the scale of implementation. Scale of implementation particularly matters when there is competition for scarce resources.

{6.3, 6.4, 6.7, 7.3, 7.4, 7.5, 7.6, 8.2, 8.4, 8.6, Figure 8.4, Table SM8.1, Table SM8.2, 9.4, 9.5, 9.8, Table 9.5, 10.3, 10.4, 10.5, 10.6, 10.8, Table 10.3, 11.5, 12.5, 17.3, Figure 17.1, Table SM17.1, Annex II Part IV Section 12}

D.2 There is a strong link between sustainable development, vulnerability and climate risks. Limited economic, social and institutional resources often result in high vulnerability and low adaptive capacity, especially in developing countries (*medium confidence*). Several response options deliver both mitigation and adaptation outcomes, especially in human settlements, land management, and in relation to ecosystems. However, land and aquatic ecosystems can be adversely affected by some mitigation actions, depending on their implementation (*medium confidence*). Coordinated cross-sectoral policies and planning can maximise synergies and avoid or reduce trade-offs between mitigation and adaptation (*high confidence*). {3.7, 4.4, 13.8, 17.3, WG II}

D.2.1 Sustainable urban planning and infrastructure design including green roofs and facades, networks of parks and open spaces, management of urban forests and wetlands, urban agriculture, and water-sensitive design can deliver both mitigation and adaptation benefits in settlements (*medium confidence*). These options can also reduce flood risks, pressure on urban sewer systems, urban heat island effects, and can deliver health benefits from reduced air pollution (*high confidence*). There could also be trade-offs. For example, increasing urban density to reduce travel demand, could imply high vulnerability to heat waves and flooding (*high confidence*). (Figure SPM.8) {3.7, 8.2, 8.4, 12.5, 13.8, 17.3}

D.2.2 Land-related mitigation options with potential co-benefits for adaptation include agroforestry, cover crops, intercropping, and perennial plants, thus restoring natural vegetation and rehabilitating degraded land. These can enhance resilience by maintaining land productivity and protecting and diversifying livelihoods. Restoration of mangroves and coastal wetlands sequester carbon, while also reducing coastal erosion and protecting against storm surges, thus, reduce the risks from sea level rise and extreme weather. (*high confidence*) {4.4, 7.4, 7.6, 12.5, 13.8}

D.2.3 Some mitigation options can increase competition for scarce resources including land, water and biomass. Consequently, these can also reduce adaptive capacity, especially if deployed at larger scale and with high expansion rates thus exacerbating existing risks in particular where land and water resources are very limited. Examples include the large-scale or poorly planned deployment of bioenergy, biochar, and afforestation of naturally unforested land. (*high confidence*) {12.5, 17.3}

D.2.4 Coordinated policies, equitable partnerships and integration of adaptation and mitigation within and across sectors can maximise synergies and minimise trade-offs and thereby enhance the support for climate action (*medium confidence*). Even if extensive global mitigation efforts are implemented, there

will be a large need for financial, technical, and human resources for adaptation. Absence or limited resources in social and institutional systems can lead to poorly coordinated responses, thus reducing the potential for maximising mitigation and adaptation benefits, and increasing risk (*high confidence*). {12.6, 13.8, 17.1, 17.3}

D.3 Enhanced mitigation and broader action to shift development pathways towards sustainability will have distributional consequences within and between countries. Attention to equity and broad and meaningful participation of all relevant actors in decision-making at all scales can build social trust, and deepen and widen support for transformative changes. (*high confidence*) {3.6, 4.2, 4.5, 5.2, 13.2, 17.3, 17.4}

D.3.1 Countries at all stages of economic development seek to improve the well-being of people, and their development priorities reflect different starting points and contexts. Different contexts include social, economic, environmental, cultural, or political conditions, resource endowment, capabilities, international environment, and history. The enabling conditions for shifting development pathways towards increased sustainability will therefore also differ, giving rise to different needs. (*high confidence*) (Figure SPM.2) {1.6, 1.7, 2.4, 2.6, Cross-Chapter Box 5 in Chapter 4, 4.3.2, 17.4}

D.3.2 Ambitious mitigation pathways imply large and sometimes disruptive changes in economic structure, with significant distributional consequences, within and between countries. Equity remains a central element in the UN climate regime, notwithstanding shifts in differentiation between states over time and challenges in assessing fair shares. Distributional consequences within and between countries include shifting of income and employment during the transition from high to low emissions activities. While some jobs may be lost, low-emissions development can also open more opportunities to enhance skills and create more jobs that last, with differences across countries and sectors. Integrated policy packages can improve the ability to integrate considerations of equity, gender equality and justice. (*high confidence*). {1.4, 1.6, 3.6, 4.2, 5.2, Box 11.1, 14.3, 15.2, 15.5, 15.6}

D.3.3 Inequalities in the distribution of emissions and in the impacts of mitigation policies within countries affect social cohesion and the acceptability of mitigation and other environmental policies. Equity and just transitions can enable deeper ambitions for accelerated mitigation. Applying just transition principles and implementing them through collective and participatory decision-making processes is an effective way of integrating equity principles into policies at all scales, in different ways depending on national circumstances. (*medium confidence*) This is already taking place in many countries and regions, as national just transition commissions or task forces, and related national policies, have been established in several countries. A multitude of actors, networks, and movements are engaged. (*high confidence*) {1.6, 1.7, 2.4, 2.6, 4.5, 13.2, 13.9, 14.3, 14.5}

D.3.4 Broadening equitable access to domestic and international finance, technologies that facilitate mitigation, and capacity, while explicitly addressing needs can further integrate equity and justice into national and international policies and act as a catalyst for accelerating mitigation and shifting development pathways (*medium confidence*). The consideration of ethics and equity can help address the uneven distribution of adverse impacts associated with 1.5°C and higher levels of global warming, in all societies (*high confidence*). Consideration of climate justice can help to facilitate shifting development pathways towards sustainability, including through equitable sharing of benefits and burdens of mitigation, increasing resilience to the impacts of climate change, especially for vulnerable countries and communities, and equitably supporting those in need (*high confidence*). {1.4, 1.6, 1.7,

3.6, 4.2, 4.5, Box 5.10, 13.4, 13.8, 13.9, 14.3, 14.5, 15.2, 15.5, 15.6, 16.5, 17.3, 17.4, SR1.5 SPM, WGII CH18}

E. Strengthening the response

E.1 There are mitigation options which are feasible [FOOTNOTE 72] to deploy at scale in the near term. Feasibility differs across sectors and regions, and according to capacities and the speed and scale of implementation. Barriers to feasibility would need to be reduced or removed, and enabling conditions [FOOTNOTE 73] strengthened to deploy mitigation options at scale. These barriers and enablers include geophysical, environmental-ecological, technological, and economic factors, and especially institutional and socio-cultural factors. Strengthened near-term action beyond the NDCs (announced prior to UNFCCC COP26) can reduce and/or avoid long-term feasibility challenges of global modelled pathways that limit warming to 1.5 °C (>50%) with no or limited overshoot. (*high confidence*) {3.8, 6.4, 8.5, 9.9, 10.8, 12.3, Figure TS.31, Annex II Part IV Section 11}

FOOTNOTE 72: In this report, the term ‘feasibility’ refers to the potential for a mitigation or adaptation option to be implemented. Factors influencing feasibility are context-dependent and may change over time. Feasibility depends on geophysical, environmental-ecological, technological, economic, socio-cultural and institutional factors that enable or constrain the implementation of an option. The feasibility of options may change when different options are combined and increase when enabling conditions are strengthened.

FOOTNOTE 73: In this report, the term ‘enabling conditions’ refers to conditions that enhance the feasibility of adaptation and mitigation options. Enabling conditions include finance, technological innovation, strengthening policy instruments, institutional capacity, multi-level governance and changes in human behaviour and lifestyles.

E.1.1 Several mitigation options, notably solar energy, wind energy, electrification of urban systems, urban green infrastructure, energy efficiency, demand side management, improved forest- and crop/grassland management, and reduced food waste and loss, are technically viable, are becoming increasingly cost effective, and are generally supported by the public. This enables deployment in many regions. (*high confidence*) While many mitigation options have environmental co-benefits, including improved air quality and reducing toxic waste, many also have adverse environmental impacts, such as reduced biodiversity, when applied at very large scale, for example very large scale bioenergy or large scale use of battery storage, that would have to be managed (*medium confidence*). Almost all mitigation options face institutional barriers that need to be addressed to enable their application at scale (*medium confidence*). {6.4, Figure 6.19, 7.4, 8.5, Figure 8.19, 9.9, Figure 9.20, 10.8, Figure 10.23, 12.3, Figure 12.4, Figure TS.31}

E.1.2 The feasibility of mitigation options varies according to context and time. For example, the institutional capacity to support deployment varies across countries; the feasibility of options that involve large-scale land use changes varies across regions; spatial planning has a higher potential at early stages of urban development; the potential of geothermal is site specific; and capacities, cultural and local conditions can either inhibit or enable demand-side responses. The deployment of solar and wind energy has been assessed to become increasingly feasible over time. The feasibility of some options can increase when combined or integrated, such as using land for both agriculture and

centralised solar production. (*high confidence*) {6.4, 6.6, 7.4, 8.5, 9.9, 10.8, 12.3, Appendix 10.3, Table SM6, Table SM8.2, Table SM9.1, Table SM12.B}

E.1.3 Feasibility depends on the scale and speed of implementation. Most options face barriers when they are implemented rapidly at a large scale, but the scale at which barriers manifest themselves varies. Strengthened and coordinated near-term actions in cost-effective modelled global pathways that limit warming to 2°C (>67%) or lower, reduce the overall risks to the feasibility of the system transitions, compared to modelled pathways with relatively delayed or uncoordinated action.[FOOTNOTE 74] (*high confidence*) {3.8, 6.4, 10.8, 12.3}

FOOTNOTE 74: The future feasibility challenges described in the modelled pathways may differ from the real-world feasibility experiences of the past.

E.2 In all countries, mitigation efforts embedded within the wider development context can increase the pace, depth and breadth of emissions reductions (*medium confidence*). Policies that shift development pathways towards sustainability can broaden the portfolio of available mitigation responses, and enable the pursuit of synergies with development objectives (*medium confidence*). Actions can be taken now to shift development pathways and accelerate mitigation and transitions across systems (*high confidence*). {4.3, 4.4, Cross-Chapter Box 5 in Chapter 4, 5.2, 5.4, 13.9, 14.5, 15.6, 16.3, 16.4, 16.5}

E.2.1 Current development pathways may create behavioural, spatial, economic and social barriers to accelerated mitigation at all scales (*high confidence*). Choices made by policymakers, citizens, the private sector and other stakeholders influence societies' development pathways (*high confidence*). Actions that steer, for example, energy and land systems transitions, economy-wide structural change, and behaviour change, can shift development pathways towards sustainability [FOOTNOTE 75] (*medium confidence*). {4.3, Cross-Chapter Box 5 in Chapter 4, 5.4, 13.9}

FOOTNOTE 75: Sustainability may be interpreted differently in various contexts as societies pursue a variety of sustainable development objectives.

E.2.2 Combining mitigation with policies to shift development pathways, such as broader sectoral policies, policies that induce lifestyle or behaviour changes, financial regulation, or macroeconomic policies can overcome barriers and open up a broader range of mitigation options (*high confidence*). It can also facilitate the combination of mitigation and other development goals (*high confidence*). For example, measures promoting walkable urban areas combined with electrification and renewable energy can create health co-benefits from cleaner air and benefits from enhanced mobility (*high confidence*). Coordinated housing policies that broaden relocation options can make mitigation measures in transport more effective (*medium confidence*). {3.2, 4.3, 4.4, Cross-Chapter Box 5 in Chapter 4, 5.3, 8.2, 8.4}

E.2.3 Institutional and regulatory capacity, innovation, finance, improved governance and collaboration across scales, and multi-objective policies enable enhanced mitigation and shifts in development pathways. Such interventions can be mutually reinforcing and establish positive feedback mechanisms, resulting in accelerated mitigation. (*high confidence*) {4.4, 5.4, Figure 5.14, 5.6, 9.9, 13.9, 14.5, 15.6, 16.3, 16.4, 16.5, Cross-Chapter Box 12 in Chapter 16}

E.2.4 Enhanced action on all the above enabling conditions can be taken now (*high confidence*). In some situations, such as with innovation in technology at an early stage of development and some changes in behaviour towards low-emissions, because the enabling conditions may take time to be established, action in the near-term can yield accelerated mitigation in the mid-term (*medium confidence*).

confidence). In other situations, the enabling conditions can be put in place and yield results in a relatively short time frame, for example the provision of energy related information, advice and feedback to promote energy saving behaviour (*high confidence*). {4.4, 5.4, Figure 5.14, 5.6, 6.7, 9.9, 13.9, 14.5, 15.6, 16.3, 16.4, 16.5, Cross-Chapter Box 12 in Chapter 16}

E.3 Climate governance, acting through laws, strategies and institutions, based on national circumstances, supports mitigation by providing frameworks through which diverse actors interact, and a basis for policy development and implementation (*medium confidence*). Climate governance is most effective when it integrates across multiple policy domains, helps realise synergies and minimize trade-offs, and connects national and sub-national policy-making levels (*high confidence*). Effective and equitable climate governance builds on engagement with civil society actors, political actors, businesses, youth, labour, media, Indigenous Peoples and local communities (*medium confidence*). {5.4, 5.6, 8.5, 9.9, 13.2, 13.7, 13.9}

E.3.1 Climate governance enables mitigation by providing an overall direction, setting targets, mainstreaming climate action across policy domains, enhancing regulatory certainty, creating specialised organisations and creating the context to mobilise finance (*medium confidence*). These functions can be promoted by climate-relevant laws, which are growing in number, or climate strategies, among others, based on national and sub-national context (*medium confidence*). Framework laws set an overarching legal basis, either operating through a target and implementation approach, or a sectoral mainstreaming approach, or both, depending on national circumstance (*medium confidence*). Direct national and sub-national laws that explicitly target mitigation and indirect laws that impact emissions through mitigation related policy domains have both been shown to be relevant to mitigation outcomes (*medium confidence*). {13.2}

E.3.2 Effective national climate institutions address coordination across sectors, scales and actors, build consensus for action among diverse interests, and inform strategy setting (*medium confidence*). These functions are often accomplished through independent national expert bodies, and high-level coordinating bodies that transcend departmental mandates. Complementary sub-national institutions tailor mitigation actions to local context and enable experimentation but can be limited by inequities and resource and capacity constraints (*high confidence*). Effective governance requires adequate institutional capacity at all levels (*high confidence*). {4.4, 8.5, 9.9, 11.3, 11.5, 11.6, 13.2, 13.5, 13.7, 13.9}

E.3.3 The extent to which civil society actors, political actors, businesses, youth, labour, media, Indigenous Peoples, and local communities are engaged influences political support for climate change mitigation and eventual policy outcomes. Structural factors of national circumstances and capabilities (e.g., economic and natural endowments, political systems and cultural factors and gender considerations) affect the breadth and depth of climate governance. Mitigation options that align with prevalent ideas, values and beliefs are more easily adopted and implemented. Climate-related litigation, for example by governments, private sector, civil society and individuals is growing, with a large number of cases in some developed countries, and with a much smaller number in some developing countries, and in some cases, has influenced the outcome and ambition of climate governance. (*medium confidence*) {5.2, 5.4, 5.5, 5.6, 9.9, 13.3, 13.4}

E.4 Many regulatory and economic instruments have already been deployed successfully. Instrument design can help address equity and other objectives. These instruments could support deep emissions reductions and stimulate innovation if scaled up and applied more widely (*high confidence*). Policy packages that enable innovation and build capacity are better able to support

a shift towards equitable low-emission futures than are individual policies (*high confidence*). Economy-wide packages, consistent with national circumstances, can meet short-term economic goals while reducing emissions and shifting development pathways towards sustainability (*medium confidence*). {13.6, 13.7, 13.9, 16.3, 16.4, 16.6, Cross-Chapter Box 5 in Chapter 4}

E.4.1 A wide range of regulatory instruments at the sectoral level have proven effective in reducing emissions. These instruments, and broad-based approaches including relevant economic instruments[FOOTNOTE 76], are complementary. (*high confidence*) Regulatory instruments that are designed to be implemented with flexibility mechanisms can reduce costs (*medium confidence*). Scaling up and enhancing the use of regulatory instruments, consistent with national circumstances, could improve mitigation outcomes in sectoral applications, including but not limited to renewable energy, land-use and zoning, building codes, vehicle and energy efficiency, fuel standards, and low-emissions industrial processes and materials (*high confidence*). {6.7, 7.6, 8.4, 9.9, 10.4, 11.5, 11.6, 13.6}

FOOTNOTE 76: Economic instruments are structured to provide a financial incentive to reduce emissions and include, among others, market- and price-based instruments.

E.4.2 Economic instruments have been effective in reducing emissions, complemented by regulatory instruments mainly at the national and also sub-national and regional level (*high confidence*). Where implemented, carbon pricing instruments have incentivized low-cost emissions reduction measures, but have been less effective, on their own and at prevailing prices during the assessment period, to promote higher-cost measures necessary for further reductions (*medium confidence*). Equity and distributional impacts of such carbon pricing instruments can be addressed by using revenue from carbon taxes or emissions trading to support low-income households, among other approaches (*high confidence*). Practical experience has informed instrument design and helped to improve predictability, environmental effectiveness, economic efficiency, distributional goals and social acceptance (*high confidence*). Removing fossil fuel subsidies would reduce emissions, improve public revenue and macroeconomic performance, and yield other environmental and sustainable development benefits; subsidy removal may have adverse distributional impacts especially on the most economically vulnerable groups which, in some cases can be mitigated by measures such as re-distributing revenue saved, all of which depend on national circumstances (*high confidence*); fossil fuel subsidy removal is projected by various studies to reduce global CO₂ emissions by 1-4%, and GHG emissions by up to 10% by 2030, varying across regions (*medium confidence*). {6.3, 13.6}

E.4.3 Low-emission technological innovation is strengthened through the combination of dedicated technology-push policies and investments (e.g., for scientific training, R&D, demonstration), with tailored demand-pull policies (e.g., standards, feed-in tariffs, taxes), which create incentives and market opportunities. Developing countries' abilities to deploy low-emission technologies, seize socio-economic benefits and manage trade-offs would be enhanced with increased financial resources and capacity for innovation which are currently concentrated in developed countries, alongside technology transfer. (*high confidence*) {16.2, 16.3, 16.4, 16.5}

E.4.4 Effective policy packages would be comprehensive in coverage, harnessed to a clear vision for change, balanced across objectives, aligned with specific technology and system needs, consistent in terms of design and tailored to national circumstances. They are better able to realise synergies and avoid trade-offs across climate and development objectives. Examples include: emissions reductions from buildings through a mix of efficiency targets, building codes, appliance performance standards, information provision, carbon pricing, finance and technical assistance; and industrial GHG emissions reductions through innovation support, market creation and capacity building. (*high confidence*) {4.4, 6.7, 9.9, 11.6, 13.7, 13.9, 16.3, 16.4}

E.4.5 Economy-wide packages that support mitigation and avoid negative environmental outcomes include: long-term public spending commitments, pricing reform; and investment in education and training, natural capital, R&D and infrastructure (*high confidence*). They can meet short-term economic goals while reducing emissions and shifting development pathways towards sustainability (*medium confidence*). Infrastructure investments can be designed to promote low-emissions futures that meet development needs (*medium confidence*). {Cross Chapter Box 7 in Chapter 4, 5.4, 5.6, 8.5, 13.6, 13.9, 16.3, 16.5, 16.6}

E.4.6 National policies to support technology development and diffusion, and participation in international markets for emission reduction, can bring positive spill-over effects for other countries (*medium confidence*), although reduced demand for fossil fuels could result in costs to exporting countries (*high confidence*). There is no consistent evidence that current emission trading systems have led to significant emissions leakage, which can be attributed to design features aimed at minimising competitiveness effects among other reasons (*medium confidence*). {13.6, 13.7, 13.8, 16.2, 16.3, 16.4}

E.5 **Tracked financial flows fall short of the levels needed to achieve mitigation goals across all sectors and regions. The challenge of closing gaps is largest in developing countries as a whole. Scaling up mitigation financial flows can be supported by clear policy choices and signals from governments and the international community. (*high confidence*) Accelerated international financial cooperation is a critical enabler of low-GHG and just transitions, and can address inequities in access to finance and the costs of, and vulnerability to, the impacts of climate change (*high confidence*).** {15.2, 15.3, 15.4, 15.5, 15.6}

E.5.1 Average annual modelled investment requirements for 2020 to 2030 in scenarios that limit warming to 2°C or 1.5°C are a factor of three to six greater than current levels, and total mitigation investments (public, private, domestic and international) would need to increase across all sectors and regions (*medium confidence*). Mitigation investment gaps are wide for all sectors, and widest for the AFOLU sector in relative terms and for developing countries [FOOTNOTE 77] (*high confidence*). Financing and investment requirements for adaptation, reduction of losses and damages, general infrastructure, regulatory environment and capacity building, and climate-responsive social protection further exacerbate the magnitude of the challenges for developing countries to attract financing (*high confidence*). {3.2, 14.4, 15.1, 15.2, 15.3, 15.4, 15.5}

FOOTNOTE 77: In modelled pathways, regional investments are projected to occur when and where they are most cost-effective to limit global warming. The model quantifications help to identify high-priority areas for cost-effective investments, but do not provide any indication on who would finance the regional investments.

E.5.2 There is sufficient global capital and liquidity to close global investment gaps, given the size of the global financial system, but there are barriers to redirect capital to climate action both within and outside the global financial sector, and in the macroeconomic headwinds facing developing regions. Barriers to the deployment of commercial finance from within the financial sector as well as macroeconomic considerations include: inadequate assessment of climate-related risks and investment opportunities, regional mismatch between available capital and investment needs, home bias factors, country indebtedness levels, economic vulnerability, and limited institutional capacities (*high confidence*). Challenges from outside the financial sector include: limited local capital markets; unattractive risk-return profiles, in particular due to missing or weak regulatory environments consistent with ambition levels; limited institutional capacity to ensure safeguards; standardization, aggregation,

scalability and replicability of investment opportunities and financing models; and, a pipeline ready for commercial investments. (*high confidence*) {15.2, 15.3, 15.5, 15.6}

E.5.3 Accelerated financial support for developing countries from developed countries and other sources is a critical enabler to enhance mitigation action and address inequities in access to finance, including its costs, terms and conditions and economic vulnerability to climate change for developing countries (*high confidence*). Scaled-up public grants for mitigation and adaptation funding for vulnerable regions, especially in Sub-Saharan Africa, would be cost-effective and have high social returns in terms of access to basic energy (*high confidence*). Options for scaling up mitigation in developing regions include: increased levels of public finance and publicly mobilised private finance flows from developed to developing countries in the context of the USD100 billion-a-year goal; increase the use of public guarantees to reduce risks and leverage private flows at lower cost; local capital markets development; and building greater trust in international cooperation processes (*high confidence*). A coordinated effort to make the post-pandemic recovery sustainable and increased flows of financing over the next decade can accelerate climate action, including in developing regions and countries facing high debt costs, debt distress and macro-economic uncertainty (*high confidence*). {15.2, 15.3, 15.4, 15.5, 15.6, Box 15.6}

E.5.4 Clear signalling by governments and the international community, including a stronger alignment of public sector finance and policy, and higher levels of public sector climate finance, reduces uncertainty and transition risks for the private sector. Depending on national contexts, investors and financial intermediaries, central banks, and financial regulators can support climate action and can shift the systemic underpricing of climate-related risk by increasing awareness, transparency and consideration of climate-related risk, and investment opportunities. Financial flows can also be aligned with funding needs through: greater support for technology development; a continued role for multilateral and national climate funds and development banks; lowering financing costs for underserved groups through entities such as green banks existing in some countries, funds and risk-sharing mechanisms; economic instruments which consider economic and social equity and distributional impacts; gender-responsive and women-empowerment programs as well as enhanced access to finance for local communities and Indigenous Peoples and small landowners; and greater public-private cooperation. (*high confidence*) {15.2, 15.5, 15.6}

E.6 International cooperation is a critical enabler for achieving ambitious climate change mitigation goals. The UNFCCC, Kyoto Protocol, and Paris Agreement are supporting rising levels of national ambition and encouraging development and implementation of climate policies, although gaps remain. Partnerships, agreements, institutions and initiatives operating at the sub-global and sectoral levels and engaging multiple actors are emerging, with mixed levels of effectiveness. (*high confidence*) {8.5, 14.2, 14.3, 14.5, 14.6, 15.6, 16.5}

E.6.1 Internationally agreed processes and goals, such as those in the UNFCCC, Kyoto Protocol, and Paris Agreement, including transparency requirements for national reporting on emissions, actions and support, and tracking progress towards the achievement of nationally determined contributions, are enhancing international cooperation, national ambition and policy development. International financial, technology and capacity building support to developing countries will enable greater implementation and encourage ambitious nationally determined contributions over time. (*medium confidence*) {14.3}

E.6.2 International cooperation on technology development and transfer accompanied by capacity building, knowledge sharing, and technical and financial support can accelerate the global diffusion of mitigation technologies, practices and policies at national and sub-national levels, and align these with

other development objectives (*high confidence*). Challenges in and opportunities to enhance innovation cooperation exist, including in the implementation of elements of the UNFCCC and the Paris Agreement as per the literature assessed, such as in relation to technology development and transfer, and finance (*high confidence*). International cooperation on innovation works best when tailored to specific institutional and capability contexts, when it benefits local value chains, when partners collaborate equitably and on voluntary and mutually agreed terms, when all relevant voices are heard, and when capacity building is an integral part of the effort (*medium confidence*). Support to strengthen technological innovation systems and innovation capabilities, including through financial support in developing countries would enhance engagement in and improve international cooperation on innovation (*high confidence*). {4.4, 14.2, 14.4, 16.3, 16.5, 16.6}

E.6.3 Transnational partnerships can stimulate policy development, low-emissions technology diffusion and emission reductions by linking sub-national and other actors, including cities, regions, non-governmental organisations and private sector entities, and by enhancing interactions between state and non-state actors. While this potential of transnational partnerships is evident, uncertainties remain over their costs, feasibility, and effectiveness. Transnational networks of city governments are leading to enhanced ambition and policy development and a growing exchange of experience and best practices (*medium confidence*). {8.5, 11.6, 14.5, 16.5, Cross-Chapter Box 12 in Chapter 16}

E.6.4 International environmental and sectoral agreements, institutions, and initiatives are helping, and in some cases may help, to stimulate low GHG emissions investment and reduce emissions. Agreements addressing ozone depletion and transboundary air pollution are contributing to mitigation, and in other areas, such as atmospheric emissions of mercury, may contribute to mitigation (*high confidence*). Trade rules have the potential to stimulate international adoption of mitigation technologies and policies, but may also limit countries' ability to adopt trade-related climate policies (*medium confidence*). Current sectoral levels of ambition vary, with emission reduction aspirations in international aviation and shipping lower than in many other sectors (*medium confidence*). {14.5, 14.6}



Bryde's Whale

Bryde's Whale

Balaenoptera edeni



Protected Status

CITES APPENDIX II

Throughout Its Range

MMPA PROTECTED

Throughout Its Range

Quick Facts

WEIGHT	About 90,000 pounds
LIFESPAN	Unknown but sexually mature at 9 years
LENGTH	40 to 55 feet
THREATS	Energy exploration, Ocean noise, Oil spills , Vessel strikes, Whaling (outside the United States)
REGION	New England/Mid-Atlantic, Pacific Islands, Southeast, West Coast



Bryde's whale swimming in the ocean. Credit: NOAA Fisheries

About the Species

Bryde's (pronounced "broodus") whales are members of the baleen whale family. They are considered one of the "great whales," or rorquals, which is a group that also includes [blue whales](#) and [humpback whales](#). Bryde's whales are named for Johan Bryde, a Norwegian who built the first whaling stations in South Africa in the early 20th century.

Bryde's whales are found in warm, temperate oceans including the Atlantic, Indian, and Pacific. Some populations of Bryde's whales make short migratory movements with the seasons, while others do not migrate, making them unique among other migrating baleen whales.

Bryde's whales are vulnerable to many stressors and threats, including vessel strikes, ocean noise, and whaling outside the United States.

All Bryde's whales are protected under the [Marine Mammal Protection Act](#).

Population Status

NOAA Fisheries estimates population size and trends in our [stock assessment reports](#). At this time, there is not enough information to estimate population trends for the Bryde's whale species as a whole.

Bryde's whales are currently considered monotypic (belonging to one species). Currently, there are two subspecies of Bryde's whales. Eden's whale (*Balaenoptera edeni*) is a smaller form found in the

Indian and western Pacific oceans, primarily in coastal waters. The Bryde's whale (*Balaenoptera edeni brydei*) is a larger form, found primarily in pelagic waters. The Bryde's whale's "pygmy form" was identified in the late 1970s and early 1980s has been described as a separate species, Omura's whale (*Balaenoptera omurai*).

Each subspecies has a different geographic distribution, genetic makeup, habitat, and physical appearance. Researchers are discussing whether the science supports recognizing the two subspecies as full species or whether additional data are needed to make that determination.

Protected Status

CITES Appendix II

- Throughout Its Range

MMPA Protected

- Throughout Its Range

Appearance

Bryde's whales look similar to [sei whales](#) but are smaller and prefer warmer waters. Unlike other rorquals, which have a single ridge on their rostrum, Bryde's whales have three prominent ridges in front of their blowhole. Their bodies are sleek and their flippers are slender and pointed.

The head of a Bryde's whale makes up about one quarter of its entire body length. The whales have a broad fluke, or tail, and a pointed and strongly hooked dorsal fin located about two-thirds back on the body. Bryde's whales have 40 to 70 throat grooves on their underside that expand while feeding and 250 to 410 gray, coarse baleen plates on each side of their mouths that act as strainers while they feed. Male Bryde's whales are usually slightly smaller than females.

Behavior and Diet

Bryde's whales are usually seen alone or in pairs. Nonetheless, there have been reports of up to 20 whales loosely grouped together in feeding areas.

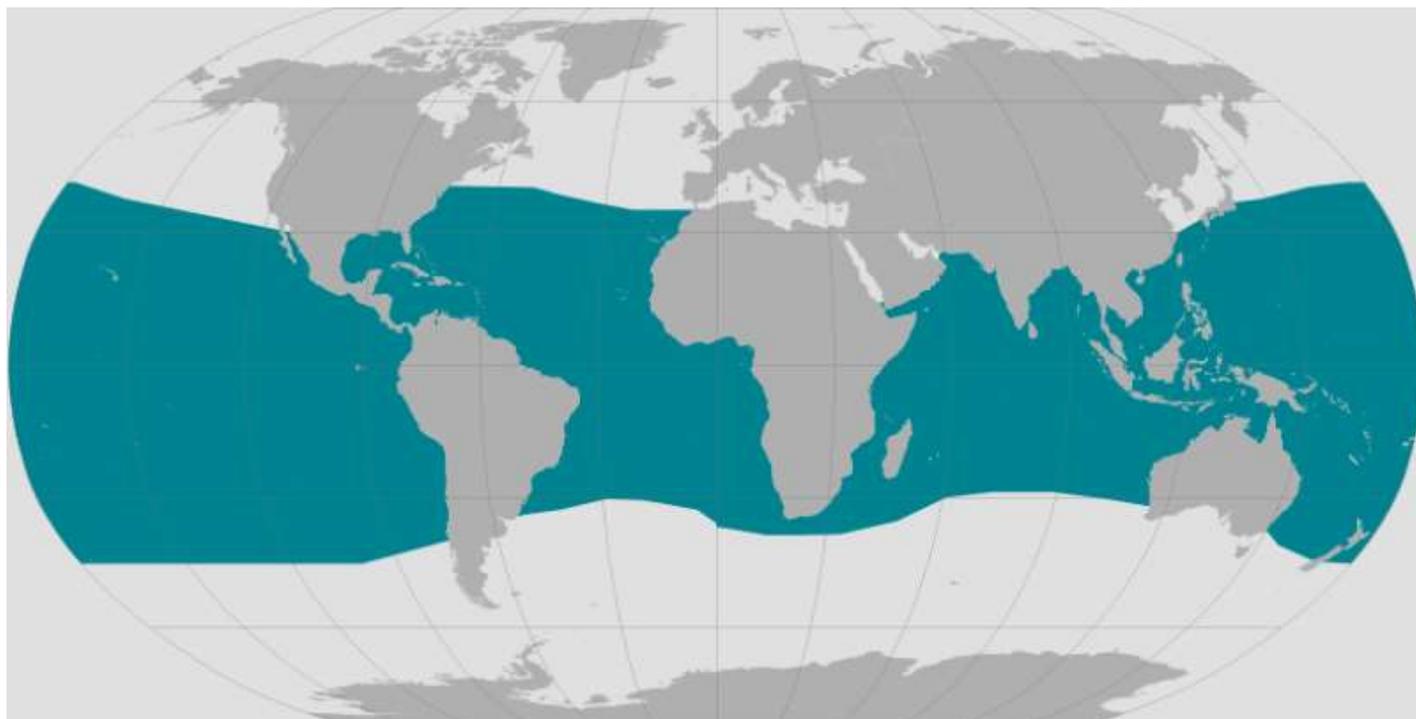
Research suggests that Bryde's whales spend most of the day within 50 feet of the water's surface. They commonly swim at 1 to 4 miles per hour but can reach speeds of 12 to 15 miles per hour. They dive for about 5 to 15 minutes, with a maximum dive duration of 20 minutes, and can reach depths up to 1,000 feet. They do not display their flukes when diving.

Bryde's whales eat an estimated 1,320 to 1,450 pounds of food per day. Their diet consists of krill, copepods, red crabs, shrimp, as well as a variety of schooling fish, such as herring, mackerel, pilchards, and sardines. Bryde's whales use different methods to feed in the water column, including skimming the surface, lunging, and creating bubble nets.

Bryde's whales can blow water 10 to 13 feet into the air when at the water's surface. They sometimes exhale while underwater as well. Additionally, Bryde's whales can change directions unexpectedly when swimming. They sometimes generate short, powerful sounds that have low frequencies and sound like "moans."

Where They Live

Bryde's whales have a wide distribution and occur in tropical, subtropical, and warm temperate waters (61° to 72°F) around the world. They live in all oceans from 40° south to 40° north. Some populations of Bryde's whales migrate with the seasons, moving away from the equator during the summer and towards the equator during the winter. Other populations of Bryde's whales are residents, meaning that they do not migrate.



World map providing approximate representation of the Bryde's whale range

Lifespan & Reproduction

Bryde's whales become sexually mature at around nine years of age and can mate year-round. The peak of the breeding and calving season occurs in autumn, and females give birth to a single calf every two to three years. Pregnancy lasts 10 to 12 months, and calves nurse for about 12 months.

Threats

Bryde's whale populations are exposed to a variety of stressors and threats, including vessel strikes, ocean noise, and whaling outside the United States.

Vessel Strikes

Accidental vessel strikes can injure or kill Bryde's whales. They are vulnerable to vessel strikes throughout their range, but the risk is much higher in coastal areas with heavy vessel traffic. Bryde's

whales are the third most commonly reported species struck by vessels in the southern hemisphere.

Ocean Noise

Low-frequency underwater noise pollution can interrupt Bryde's whales' normal behavior by hindering their ability to use sound, causing a disruption of their ability to communicate, choose mates, find food, avoid predators, and navigate.

Whaling (Outside the United States)

Historically, Bryde's whales were not major targets for commercial whaling. However, whalers have recently hunted Bryde's whales off the coasts of Indonesia and the Philippines. Additionally, some hunters in Japan continue to take Bryde's whales as part of their scientific research whaling program.

Scientific Classification

Kingdom	Animalia
Phylum	Chordata
Class	Mammalia
Order	Cetacea
Family	Balaenopteridae
Genus	<i>Balaenoptera</i>
Species	<i>edeni</i>

Last updated by NOAA Fisheries on 04/21/2022

What We Do

Conservation & Management

All Bryde's whales are protected under the Marine Mammal Protection Act. Our work supports the protection and conservation of the Bryde's whale by:

- Minimizing the effects of vessel disturbance, noise, and other types of human effects
- Responding to stranded Bryde's whales

- Educating the public about Bryde's whales and the threats they face

[Learn more about our conservation efforts >](#)

Science

NOAA Fisheries conducts scientific research to learn more about the biology, behavior, and ecology of Bryde's whales to better inform management and policy. Our work includes:

- Stock assessments
- Monitoring population abundance and distribution

[Learn more about our research >](#)

How You Can Help

Reduce Speed and Be on the Lookout

Vessel collisions are a major cause of injury and death for whales. Here are some tips to avoid collisions:

Be Whale Aware. Know where whales occur (habitat).

Watch your speed in areas of known marine mammal occurrence. Keep speeds to 10 knots or less to reduce potential for injury.

Keep a sharp lookout. Look for blows, dorsal fins, tail flukes, etc. However, be aware that most captains report never seeing a whale prior to colliding with it.

Protect your boat, protect your passengers. Boats can be heavily damaged and even "totalled" after colliding with a large whale. Collisions can also injure passengers.

Keep your distance. Stay at least 100 yards away.

Stop immediately if within 100 yards. Slowly distance your vessel from the whale.

[Learn more about vessel strikes >](#)

Keep Your Distance

Be responsible when viewing marine life in the wild. Observe all large whales from a safe distance of at least 100 yards and limit your time spent observing to 30 minutes or less.

[Learn more about our marine life viewing guidelines >](#)

Report Marine Life in Distress

Report a sick, injured, entangled, stranded, or dead animal to make sure professional responders and scientists know about it and can take appropriate action. Numerous organizations around the country are trained and ready to respond. Never approach or try to save an injured or entangled animal yourself—it can be dangerous to both the animal and you.

[Learn who you should contact when you encounter a stranded or injured marine animal >](#)

Report a Violation

Call the NOAA Fisheries Enforcement Hotline at **(800) 853-1964** to report a federal marine resource violation. This hotline is available 24 hours a day, 7 days a week for anyone in the United States.

You may also contact your closest [NOAA Office of Law Enforcement field office](#) during regular business hours.

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Last updated by NOAA Fisheries on 04/21/2022

Last updated by NOAA Fisheries on 04/21/2022

In the Spotlight

Last updated by NOAA Fisheries on 04/21/2022

Management Overview

All Bryde's whales are protected under the [Marine Mammal Protection Act](#).



Bryde's whale with various wounds from predators. Credit: NOAA Fisheries

Conservation Efforts

Reducing Vessel Strikes

Collisions between whales and large vessels can injure or kill the whales and damage the vessels, but they often go unnoticed and unreported. The most effective way to reduce collision risk is to keep whales and vessels apart.

[Learn more about reducing vessel strikes >](#)

Addressing Ocean Noise

Low-frequency underwater noise may threaten Bryde's whales by interrupting their normal behavior and driving them away from areas important to their survival, such as feeding waters. Mounting evidence suggests that exposure to intense underwater sound in some settings may cause some whales to strand and ultimately die. NOAA Fisheries is investigating all aspects of acoustic communication and hearing in marine animals, as well as the effects of sound on whale behavior and hearing. In 2016, we [issued technical guidance](#) for assessing the effects of anthropogenic (human-caused) sound on marine mammal hearing.

[Learn more about ocean noise >](#)

[Learn more about underwater noise and marine life >](#)

Overseeing Marine Mammal Health and Stranding Response

We work with volunteer networks in all coastal states to respond to marine mammal strandings including all whales. When stranded animals are found alive, NOAA Fisheries and our partners assess the animal's health and determine the best course of action. When stranded animals are found dead, our scientists work to understand and investigate the cause of death. Although the cause often remains unknown, scientists can sometimes attribute strandings to disease, harmful algal blooms, vessel strikes, fishing gear entanglements, pollution exposure, and underwater noise. Some strandings can serve as indicators of ocean health, giving insight into larger environmental issues that may also have implications for human health and welfare.

[Learn more about the Marine Mammal Health and Stranding Response Program >](#)

Marine Mammal Unusual Mortality Events

Bryde's whales have never been part of a declared unusual mortality event. Under the [Marine Mammal Protection Act](#), an unusual mortality event is defined as "a stranding that is unexpected; involves a significant die-off of any marine mammal population; and demands immediate response." To understand the health of marine mammal populations, scientists study unusual mortality events.

[Get information on active and past UMEs >](#)

[Get an overview of marine mammal UMEs >](#)

Regulatory History

All marine mammals, including Bryde's whales, are protected in the United States under the MMPA.

Key Actions and Documents

Actions & Documents

Incidental Take

Final Rule to List Rice's Whale in the Gulf of Mexico Under the ESA

On April 15, 2019, NOAA Fisheries issued a final rule to list the Gulf of Mexico Bryde's whale (*Balaenoptera edeni*) as an endangered subspecies under the Endangered Species Act (ESA). On August 23, 2021, we issued a direct final rule to revise the...

- › [Direct Final Rule to Revise Taxonomy and Common Name \(86 FR 47022, 08/23/2021\)](#)
- › [Final Rule \(84 FR 15446, 04/15/2019\)](#)
- › [Notice Reopening Public Comment \(82 FR 9707, 02/08/2017\)](#)
- › [Proposed Rule \(81 FR 88639, 12/08/2016\)](#)
- › [Direct Final Rule to Revise Taxonomy and Common Name \(86 FR 47022, 08/23/2021\)](#)
- › [Status review of Bryde's whales in the Gulf of Mexico under the Endangered Spec...](#)

Final Rule

, [Southeast](#)

EFFECTIVE

May 15, 2019

Last updated by NOAA Fisheries on 04/21/2022

Science Overview

NOAA Fisheries conducts research activities on the biology, behavior, and ecology of the Bryde's whale. The results are used to inform management decisions for this species.



Bryde's whale observed during the Hawaiian Islands Cetacean and Ecosystem Assessment Survey. Credit: NOAA Fisheries/J. Cotton

Stock Assessments

Determining the size of Bryde's whale populations helps resource managers determine the success of conservation measures. Our scientists collect population information and present the data in [annual stock assessment reports](#).

Acoustic Science

Acoustics is the science of how sound is transmitted. NOAA researchers measure the acoustic environment of cetaceans to increase our understanding of the basic acoustic behavior of whales, dolphins, and fish; mapping the acoustic environment; and developing better methods to locate cetaceans using [autonomous gliders and passive acoustic arrays](#).

[Learn more about acoustic science >](#)

Last updated by NOAA Fisheries on 04/21/2022

Documents

DOCUMENT

Rice's Whale Recovery Outline

This document serves as an interim guidance document to direct recovery efforts for the Rice's...

Southeast

DOCUMENT

Status Review of Bryde's Whales in the Gulf of Mexico Under the Endangered Species Act

This status review responds to a September 18, 2014 petition from the Natural Resources Defense...

Southeast

[More Documents >](#)

Last updated by NOAA Fisheries on 04/21/2022

ENERGY TRANSITION | LNG | NATURAL GAS — 03 Jan 2022 | 19:12 UTC

Rio Grande LNG project final investment decision delayed to second half of 2022



Author [Harry Weber](#) 
Editor [Derek Sands](#) 
Commodity [Energy Transition](#), [LNG](#), [Natural Gas](#)

HIGHLIGHTS

US developer's prior target was by end of 2021

Talks with Asia, Europe buyers said to be advancing

NextDecade has delayed an expected final investment decision related to its proposed Rio Grande LNG export project in Texas to the second half of 2022, an investor presentation posted Jan. 3 on the company's website said.

The company had previously targeted a decision on a first phase consisting of at least two liquefaction trains by the end of 2021.

The adjusted timing comes as NextDecade continues to seek sufficient supply deals with buyers to support the cost of construction. To date, it has secured a single long-term contract, with Royal Dutch Shell, covering 2 million mt/year of the about 11 million mt/year of supply that is expected to make up the first phase of the project in Brownsville. The full project, as currently proposed, would involve five trains and 27 million mt/year of capacity.

During 2021, there was a flurry of commercial activity tied to current and proposed US LNG export terminals. The main beneficiaries were Cheniere Energy and Venture Global LNG, especially with Chinese buyers as high spot prices in end-user markets spurred new term deals that carry a lower fixed price. Two proposed US projects were scrapped during the year – Pembina's Jordan Cove in Oregon and Exelon-backed Annova LNG, which was to be built in Brownsville near NextDecade's site.

In its new investor presentation, NextDecade said negotiations were "advancing with multiple counterparties in Europe and Asia" and that financing would "commence" upon execution of additional sale and purchase agreements. It did not elaborate. A company official did not immediately respond to a message seeking further comment.

NextDecade has said it plans to advance a carbon capture and storage project shortly after it sanctions the first phase of the liquefaction terminal. NextDecade is also partnering with a Colorado company to measure and report the greenhouse gas intensity of the LNG to be produced at the export facility. The goal of the reporting initiative includes enabling the development of responsibly sourced natural gas from producers in the Permian Basin and Eagle Ford shale that will be fed to the terminal.

In November, NextDecade pitched to US regulators a limited amendment to its federal authorization for the LNG terminal that would allow it to voluntarily capture and store CO₂ produced at the facility. That proposal came as a federal appeals court found fault with the original Federal Energy Regulatory Commission authorization for the LNG project, remanding FERC's orders to the commission without vacating them.

NextDecade expects to receive FERC approval in 2022 for the CCS project, according to the new investor presentation.

File [The Race Gap in Residential Energy Expenditures.pdf] cannot be converted to PDF. (To download this file in its original format, please use the filename hyperlink from your search results. If you continue to experience difficulties, or to obtain a PDF generated version of files, please contact the helpdesk at ferconlinesupport@ferc.gov, or, call 866-208-3676 from 9AM to 5PM EST, weekdays. Please allow at least 48 hours for your helpdesk request to be processed.)

IEEFA U.S.: Booming U.S. natural gas exports fuel high prices

U.S. is exporting natural gas, and importing price volatility

As fall utility bills start hitting people’s mailboxes, more households will start feeling the pinch of higher natural gas prices. The wholesale price of U.S. gas has roughly tripled from last summer’s lows, and utilities are passing on rising costs to their customers. But it’s not just householders who will feel the pinch. Businesses are complaining, too: In September, an industry trade group [urged the federal government](#) to take swift action to halt the rise in natural gas prices.

This raises a key question: Why have natural gas prices risen so high, so fast?

First, a bit of context. Today’s gas prices may seem high, but that’s mostly because Americans have gotten accustomed to cheap fuel. Since 2011, natural gas prices have averaged about \$3.50/MMBtu. Prices fell below \$2/MMBtu last summer, in the depths of the COVID-19 crisis (One MMBtu, or 1 million British thermal units, has as much energy as about 8 gallons of gasoline). Yet in the first decade of the millennium, natural gas prices averaged nearly \$8 per MMBtu, after adjusting for inflation. So today’s price—\$5.52/MMBtu at press time—may seem exorbitant, but it would have seemed like a relief virtually any time from 2002 through 2009.

Why have natural gas prices risen so high, so fast?

Still, a history lesson offers cold comfort to today’s energy consumers, who are looking for the reasons behind surging heating and power bills.

Supply and Demand

Prices rarely stray far from the fundamentals of supply and demand. When supplies dip or demand spikes, prices tend to respond. Energy prices are particularly sensitive to tiny imbalances between output and consumption. Even small shortfalls or surpluses can lead to dramatic price swings. The price spikes we’ve seen over the past several months suggest that either demand has ticked up or supply has dipped, or perhaps both.

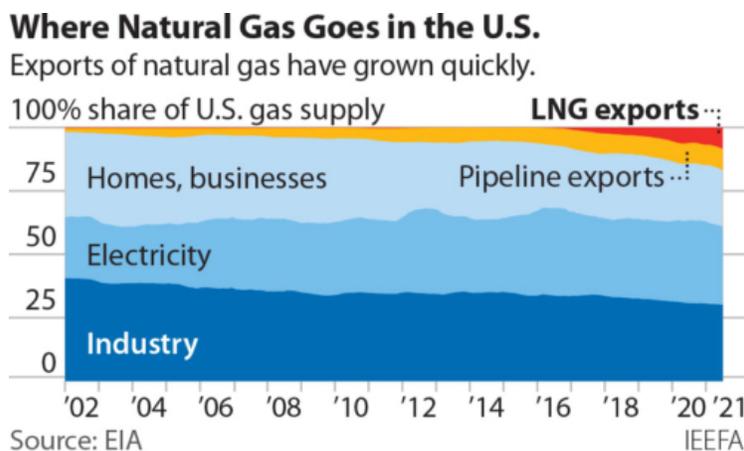
But within the U.S., gas demand has actually *fallen* a bit since pre-COVID days. For the 12 months leading up to July 2021—the most recent month for which U.S. data has been released—[total gas consumption](#) had fallen about 2% from its pre-COVID levels. So we can’t point to surging U.S. gas consumption to explain spiking prices.

The U.S. is exporting more and more natural gas, and importing higher prices as a result.

U.S. gas [production](#) has also dipped, and by just a smidge more than consumption. Most of that decline can be traced to a single month: February 2021, when the Big Freeze [halved Texas gas output](#), depleting gas storage and setting the stage for a late winter price surge. Yet today, [gas storage](#) remains just a hair under the five-year average—nothing that would explain the dramatic price spikes in summer and fall.

If an event as momentous as the Big Freeze can’t explain sky-high prices, what can? What’s changed between last year and this year to cause prices to triple?

There is one trend that’s been big enough to explain rising gas prices: The U.S. is exporting more and more natural gas, and importing higher prices as a result.



Over the past five years, U.S. exports of gas by pipeline, primarily to Mexico, have grown modestly. But that increase was dwarfed by the growth in shipments of LNG (liquefied natural gas) from six newly-commissioned facilities in Texas, Louisiana, and the East Coast. LNG is just ordinary gas chilled to -162° Celsius and pressurized so that it can be shipped in specialized ocean-going vessels. Five years ago, the U.S. exported essentially no LNG. But so far this year, LNG exports amounted to about 10 percent of total U.S. gas production.

Combining both pipeline exports and LNG shipments, exports now account for almost one-fifth of all U.S. gas demand. That share is only slated to grow as new LNG facilities come online over the next few years, and as gas exports to Mexico through existing pipelines ramp up.

For now, U.S. LNG is quite profitable. Spot LNG prices have spiked above \$30/MMBtu, reaching all-time highs in both Europe and Asia. Even with U.S. wholesale gas prices above \$5/MMBtu, it’s still quite profitable to liquefy U.S. gas and ship it to gas-hungry overseas markets.

The reasons for spiking international gas prices are myriad: Rising global LNG demand; a combination of [global supply disruptions and bad weather](#); shortfalls in [Chinese coal production](#); and [reputed Russian manipulation of European gas markets](#), reportedly to speed the approval of the new Nord Stream 2 pipeline. But

regardless of the specifics behind the international LNG price spikes, buyers in Europe and Asia are now bidding up the price of U.S. gas, and U.S. consumers are paying more as a result.

Don't expect U.S. gas producers to come to the rescue. America's gas industry has been losing money for so long that Wall Street has lost patience with it. In the past, oil and gas companies would respond to high prices by boosting output—and the resulting oversupply would lower prices and kill profits. Investors are refusing to play that game again. They're keeping their money on the sidelines, withholding money from publicly traded gas drillers that threaten to overproduce. Companies that have spare cash from gas sales are using it to pay down debts or reward investors, rather than boosting drilling. We can see this clearly in the data for Appalachia, America's biggest gas-producing region. Drilling in the region has stayed roughly flat since February, despite rising prices.

Buyers in Europe and Asia are now bidding up the price of U.S. gas, and U.S. consumers are paying more.

For America's fossil fuel industry, high natural gas prices are a feature, not a bug. In fact, fossil fuel interests predicted long ago that rising LNG exports would boost domestic gas prices. In 2016, just before the first wave of LNG projects was competed, the late coal magnate Bob Murray urged then-candidate Donald Trump to support LNG exports. As one writer put it, "The hope is if more natural gas can be exported, it might reduce the glut in the U.S., which has driven prices so low that it's killing coal."

If that was the strategy all along, it seems to be working. U.S. markets are no longer saturated with gas, prices have risen, and some utility companies have switched, albeit modestly, from gas back to coal. U.S. gas companies are making profits from the LNG they sell to Asia—but they're making even bigger profits from higher prices they're charging U.S. consumers.

The idea that LNG exports are boosting U.S. prices has now become something close to conventional wisdom among energy analysts. In late September, RBN Energy argued that LNG exports hitch U.S. gas markets to soaring international prices, and the problem is likely to get worse as more LNG export facilities come online. "The U.S.'s LNG export capacity ceiling is likely the only thing reining in Henry Hub prices from following European and Asian gas/LNG prices to the moon," the energy analytics firm said. (That ceiling will rise early next year as facilities in Texas and Louisiana expand their operations.)

Industrial gas users made the same argument, recently urging the U.S. Department of Energy to place a hold on all existing, pending, and pre-filing permits and approvals on LNG export facilities in the continental U.S. to stem increases in domestic prices. A report by Natural Gas Intelligence suggested that gas exports would increase 16 percent to 18 percent this winter, while production was slated to grow only 4 percent, setting the stage for higher gas prices. The Center for Strategic and International Analysis piled on, arguing there was now "strong evidence that exports are the primary demand driver for U.S. gas and thus the increase in prices."

But what's good news in the short term for the gas industry's bottom line could be bad news for the industry's long-term future. High and volatile gas prices are making renewables—whose costs keep falling—all the more attractive. Utilities, businesses, and industries making long-term decisions about their capital budgets can no longer be certain what gas prices will look like in five to 10 years. The price uncertainty of gas weighs in favor of the predictability of wind and solar. Sure, the sun doesn't always shine and the wind doesn't always blow, but when they do, they're completely free.

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Winter Energy Market and Reliability Assessment

2021-2022

A Staff Report to the Commission

October 21, 2021



FEDERAL ENERGY REGULATORY COMMISSION

Office of Energy Policy and Innovation

Office of Electric Reliability

This report is a product of the Federal Energy Regulatory Commission Staff. The views expressed in this report, if any, do not necessarily reflect the views of the Commission or any Commissioner.

Preface

The 2021-2022 Winter Energy Market and Reliability Assessment (Winter Assessment) provides staff's outlook for energy markets and electric reliability, focusing on the period of November 2021 through February 2022. The report is divided into four main sections. The first section discusses the February 2021 winter storm. The second section summarizes weather forecasts for the upcoming winter. The third section summarizes electricity and natural gas market fundamentals expected for winter 2021-2022. The last section discusses considerations for the upcoming winter, including winter readiness recommendations from the 2021 Cold Weather Inquiry (Joint Inquiry); natural gas dependence in New England; and interregional transfer capacity.

This report uses preliminary data from the North American Electric Reliability Corporation's (NERC) Winter Reliability Assessment and Long Term Reliability Assessment. The final version of NERC's Long Term Reliability Assessment is scheduled for publication in late 2021.

The Winter Assessment is a joint report from the Office of Energy Policy and Innovation's Division of Energy Market Assessments and the Office of Electric Reliability's Division of Engineering and Logistics.

Key Findings

This section summarizes the February 2021 winter storm along with the weather outlook for the United States (U.S.). It then summarizes the market fundamentals expected for the U.S. electricity markets and natural gas markets during winter 2021-2022 followed by considerations for the upcoming winter.

Winter 2020-2021 was particularly challenging for some regions of the U.S., highlighting the importance of winter preparedness. Of note, extreme, prolonged cold in February 2021 had significant impacts on natural gas and electric markets, leading to power outages and record high natural gas and electric prices. The Federal Energy Regulatory Commission (FERC or the Commission) and NERC staff presented key takeaways from the Joint Inquiry at the September 2021 FERC Open Meeting with a final report to follow later. The Joint Inquiry noted six preliminary findings and 28 preliminary recommendations, as discussed in the next section.¹

Temperatures have a significant impact on demand for natural gas and electricity, and higher than average temperatures are expected for the coming winter in many regions. The U.S. National Oceanic and Atmospheric Administration (NOAA) forecasts for November 2021 through February 2022 suggest above normal temperatures for most parts of the country, including New England, the Southeast, the Southwest, the Central U.S., the Rockies, and much of the Northwest and below normal temperatures for parts of the Midwest and the Pacific Northwest. Higher than average temperatures during the winter season typically imply lower than average demand for electricity and natural gas, but severe cold weather events that drive up energy demand may still occur.

Regarding market fundamentals for U.S. electricity markets, NERC forecasts net demand for electricity to increase by approximately 1% for winter 2021-2022 relative to last winter's levels, with a slight increase in

¹ FERC, NERC, *February 2021 Cold Weather Grid Operations: Preliminary Findings and Recommendations Presentation*, (September 23, 2021).

demand in the Florida subregion of SERC Reliability Corporation (SERC), the Electric Reliability Council of Texas (ERCOT), and the Northwest Power Pool (NWPP) subregion of Western Electricity Coordinating Council (WECC). Even with this demand increase, the anticipated reserve margins are projected to be sufficient for all markets and regions.

Nationally, from March 2021 through February 2022, electric capacity additions are expected to total approximately 42.4 gigawatts (GW), the majority of which are expected to come from 16.3 GW of solar and 16 GW of wind resources. During the same period, electric capacity retirements are expected to total over 7.6 GW, which include approximately 5.1 GW of coal-fired generation capacity retirements, largely in Midcontinent Independent System Operator (MISO). For November 2021 through February 2022, electric generation's demand for natural gas (power burn) is expected to average 25.3 billion cubic feet per day (Bcf), 8% below levels observed last winter, with the share of electricity generation output provided by natural gas expected to decline to 32%, down two percentage points from last winter, as of October 13, 2021. Electricity generation output forecasts for winter 2021-2022 also show the expected share of electric output from coal-fired generation to increase by about one percentage point and from renewable generation to increase by about 1.6 percentage points compared to winter 2020-2021. The forecasted drop in the share of electricity generation output provided by natural gas is due to natural gas-to-coal fuel switching in the power sector due to expected higher natural gas prices this winter and increases in the share of electricity generated from renewables as they continue to grow. That said, there are some differences among the various regions of the U.S. The proportion of electricity generated from natural gas is expected to decline in the regions of the California Independent System Operator (CAISO), ERCOT, the Southwest Power Pool (SPP), the Midcontinent Independent System Operator (MISO), and the Southeast relative to their respective 5-year averages due to higher natural gas prices. However, the regions of ISO New England (ISO-NE), New York Independent System Operator (NYISO), PJM Interconnection (PJM), and other western regions are expecting an above average share of generation output from natural gas.

Regarding market fundamentals for natural gas markets in the U.S., winter 2021-2022 natural gas production is expected to increase to 94 Bcf, a 3.2 Bcf increase from average winter 2020-2021 production. The expected increase would contrast with last year's decline in domestic natural gas production. Natural gas prices are also expected to increase across the U.S., with futures prices at Henry Hub (national benchmark in Louisiana) as of October 13, 2021 averaging \$5.63 per million British Thermal Units (MMBtu) for November 2021 through February 2022, a \$2.85/MMBtu, or 103%, increase compared to winter 2020-2021 settled futures prices. As of October 13, 2021, winter 2021-2022 futures prices at the Algonquin Citygate hub, outside Boston, are at \$18.18/MMBtu, which are the highest prices expected this winter across major hubs. This increase in futures prices at the Algonquin Citygate hub is being driven by a variety of factors; these include, but are not limited to, the winter-peaking New England region's limited natural gas pipeline capacity and competition for global liquefied natural gas (LNG) cargoes in light of rising global LNG prices and demand. As of October 2021, natural gas demand is forecast to average 111 Bcf for winter 2021-2022, a 2.5% increase above winter 2020-2021. This forecasted demand increase primarily is due to an anticipated increase of 21% in LNG exports relative to last winter. In addition, demand for natural gas in the commercial, residential, and industrial/other sectors is expected to increase during November 2021 to February 2022 compared to the same period last winter. However, power burn is expected to decline by 8% during winter 2021-2022 compared to winter 2020-2021. Further, the Energy Information Administration (EIA) forecasts natural gas storage inventories to begin the winter withdrawal season below the five-year average at 3,572 billion cubic feet (or bcf), 5% below the five-year average. In addition to lower-than-average natural gas storage inventory levels going into this winter, storage levels for propane, an alternate form of winter heating fuel, will start this winter 20% below the five-year average.

Moreover, the availability of natural gas to fuel electric power generation may have an impact on maintaining reliability of the bulk power system this winter, particularly in the New England region. In these circumstances, oil-based dual-fuel system generators, which can switch between natural gas and oil and benefit from onsite storage, could help mitigate reliance on natural gas during supply shortages or periods of high natural gas prices. In addition, rising global LNG demand is expected to have a significant impact on the limited LNG import market in New England. LNG imports supplying New England limit the impact of pipeline capacity constraints in the region. High expected natural gas prices in New England this winter could incentivize more LNG imports into the region.

Finally, exchanges between regions may also support electric markets and reliability this winter. Having additional transfer capacity allows regions to exchange power economically and to support neighbors during extreme weather events. For example, PJM, with access to Appalachian natural gas and electric interconnections to its west, south, and north, has helped adjacent regions during major weather events. Similarly, NYISO stands to potentially benefit from transfer capacity with PJM, Canada, and ISO-NE. In the Western Interconnection, CAISO has strong integration with neighboring Balancing Authorities, including members of its Energy Imbalance Market (EIM).

February 2021 Winter Storm

The February 2021 winter storm affected millions of electricity customers in ERCOT, SPP, and MISO as extreme and prolonged winter weather drove up natural gas and electricity demand for heating and led to widespread outages of critical natural gas and electric infrastructure. The controlled firm load shed event that followed was the largest in U.S. history, with a total of more than 23 GW of load shed. From February 10-19, 2021, a cold-air outbreak across the central U.S. brought freezing temperatures, snow, and ice. According to NOAA, it was the coldest event across the continental U.S. in more than 30 years (see Figure 1).² Extreme cold weather is becoming a more common occurrence in the U.S. in the recent past. In fact, the February 2021 winter storm is the fourth winter storm in the past 10 years that jeopardized bulk power system reliability.³ Together, freezing issues and fuel issues accounted for 75% of the unplanned generator outages and derates, or failures to start, resulting in energy and transmission emergencies.⁴ During the event, shut-ins and unplanned outages of natural gas wellheads, as well as unplanned outages of gathering and processing facilities, resulted in a decline of natural gas available for supply and transportation to many natural gas-fired generating units in the south-central U.S.⁵ As a result, natural gas and electricity prices reached record highs.

² NOAA National Centers for Environmental Information, *State of the Climate: National Climate Report for February 2021*, (March 2021), <https://www.ncdc.noaa.gov/sotc/national/202102> (accessed October 15, 2021).

³ FERC, NERC, *February 2021 Cold Weather Grid Operations: Preliminary Findings and Recommendations Presentation*, (September 23, 2021), Slide 3.

⁴ *Id.*, Slide 8.

⁵ *Id.*, Slide 4.

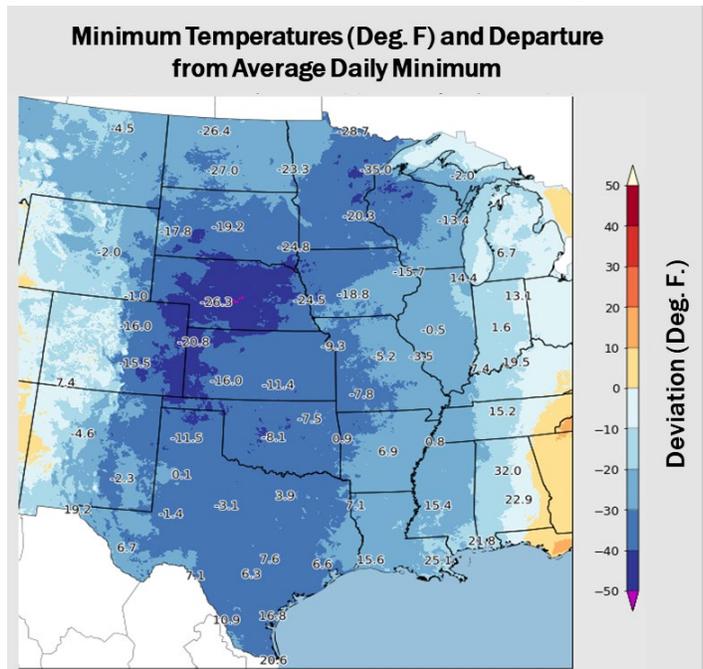
From February 8 through February 20, 2021, of the 1,293 unplanned generating unit outages, derates, and failures to start that were due to fuel issues, 1,121 (87%) were due to natural gas fuel supply issues. Natural gas fuel supply issues included the combined effects of decreased natural gas production, the specific terms and conditions of natural gas commodity and pipeline transportation contracts, and other issues like low pressure. Natural gas fuel supply issues led to a total of 357 individual natural gas-fired generating units experiencing either an outage, a derate, or a failure to start (185 units in ERCOT, 141 units in SPP, and 31 units in MISO/MISO South).⁶

Between February 15 and 18, ERCOT, MISO, and SPP Balancing Authorities needed to implement energy emergency measures including firm load shed within their respective footprints.⁷ MISO’s and SPP’s ability to transfer power (see Interregional Transfer Capacity below) through their many transmission ties with adjacent Balancing Authorities in the Eastern Interconnection helped to alleviate their generation shortfalls, preventing more severe firm load shed. ERCOT, unlike MISO and SPP, did not have the ability to import many thousands of megawatt (MW) from the Eastern Interconnection. Had ERCOT been able to import more power, it would have decreased the amount that MISO and SPP would have been able to import.⁸

During this same period, ERCOT faced 34 GW of generation outages over two consecutive days, equivalent to nearly half of ERCOT’s 2021 actual all-time winter peak load, with manual firm load shed varying from 10 to 20 GW from February 15 through February 16, 2021.⁹ While this was ongoing, ERCOT coordinated with SPP about which Balancing Authority would rely on switchable generation, accessible to either Interconnection, that both regions depend on as capacity resources.¹⁰

Following the event, the Commission and NERC announced a joint inquiry with the Regional Entities, to “examine the root causes of the reliability events that have occurred throughout the country, in particular the

Figure 1: Cold Weather Conditions – February 15, 2021



Source: U.S. National Oceanic and Atmospheric Administration

⁶ *Id.*, Slide 9.

⁷ *Id.*, Slide 6.

⁸ *Id.*, Slide 7.

⁹ *Id.*, Slide 5.

¹⁰ *Id.*, Slide 14.

regions served by ERCOT, MISO and SPP.”¹¹ Overall, the Joint Inquiry has presented 28 preliminary recommendations in total, with nine key recommendations, including Reliability Standards changes, and five recommendations for further study. These are recommended to be implemented between winter 2021-2022 and winter 2023-2024 although the implementation of some of these recommendations could extend beyond this timeframe.¹² For this winter, the Joint Inquiry’s preliminary recommendations include identifying and communicating reliability risks of natural gas fuel contracts, joint discussions between NERC, FERC, and the Regional Entities on improvements to generator winter readiness, and the inclusion of freeze protection maintenance measures in winter planning (see Winter Readiness below). The Commission and NERC plan to finalize the recommendations in late 2021.

Weather Outlook

Weather is a fundamental determinant of energy demand and supply, as below freezing temperatures increase heating demand and can stress natural gas and electric infrastructure. Like last year, NOAA forecasts that this winter will be mild for most of the country compared to NOAA’s 1991-2020 U.S. Climate Normals. However, there is a small probability that winter 2021-2022 will be slightly colder than winter 2020-2021 in part because winter 2020-2021 was warmer than forecasted in the densely populated Northeast.¹³

Figure 2 depicts the relative probabilities for above or below normal temperatures for regions across the U.S. this upcoming winter compared to NOAA’s 1991-2020 U.S. Climate Normals. The three-month NOAA outlook for November 2021, December 2021, and January 2022 assesses a 70-80% probability of above normal temperatures near Arizona, New Mexico, and West Texas. Similarly, NOAA assesses a 60-70% probability of above average temperatures in New England, the Southeast, the Gulf Coast, and the Southwest including California. NOAA assesses a 50-60% probability for above normal temperatures throughout the Carolinas, the Ohio River Valley, the Midwest, the Ozarks, the Rockies, Northern California, and Southern Oregon. NOAA assesses the upper Midwest and some of the Northwest to have an equal chance of above normal and below normal temperatures.

¹¹ *Id.*, Slide 2.

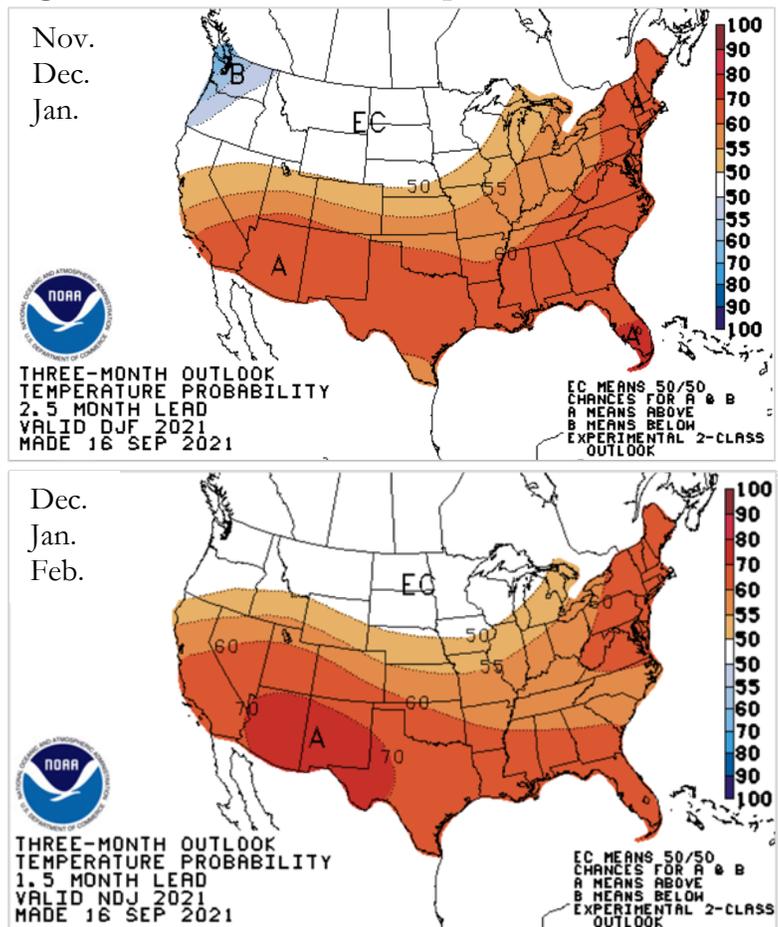
¹² *Id.*, Slide 15.

¹³ EIA, *Winter Fuels Outlook 2021-2022*, p. 21 October 2021. (Showing fewer population-weighted heating degree days during winter 2020-2021 compared to most recent years, the winter 2020-2021 forecast, and the winter 2021-2022 forecast.) *See also*, NOAA, *Winter Outlook 2020-2021: A Look Back*, March 2021.

Similar patterns persist in the three-month NOAA outlook for December 2021, January 2022, and February 2022. The probability of above average temperatures increases in Florida and the Southeast and decreases in some parts of the West. NOAA assesses a 50-55% probability of below average temperatures in the Pacific Northwest in late winter.

Higher than average temperatures during the winter season typically imply lower than average demand for electricity and natural gas, but severe cold weather events that drive up energy demand may still occur. This forecast does not address the possibility of the severe winter storms associated with a weak arctic polar vortex¹⁴ like the February 2021 winter storm or the magnitude which forecasted temperatures diverge from the Climate Normals. As an example, last year’s NOAA forecast showed an even greater probability of milder conditions in regions that were ultimately affected by the February 2021 winter storm. Forecasts for arctic oscillation – an index representing the arctic polar vortex – are only available fourteen days ahead of time, making it difficult to forecast far in advance whether a similar winter storm event will happen again this year.

Figure 2: Winter 2021/2022 Temperature Forecast



Source: National Oceanic and Atmospheric Administration

Energy Market Fundamentals

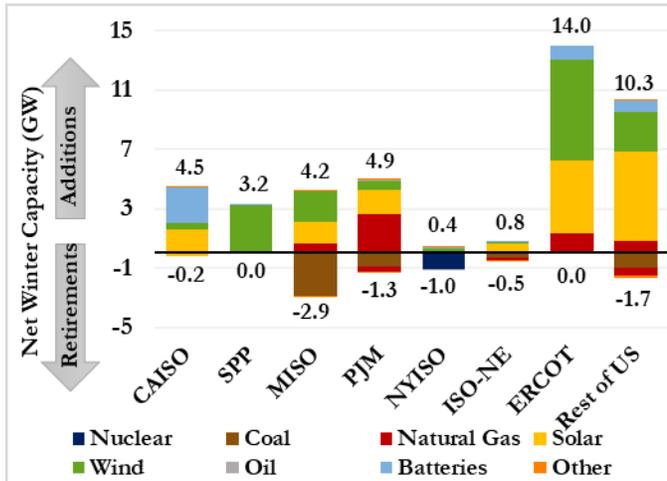
This section of the report summarizes electricity and natural gas market fundamentals expected for winter 2021-2022, including electric capacity, reserve margins, resource adequacy, peak load forecasts, and net transfers; natural gas prices, demand, production, exports, and imports; and natural gas and propane storage inventories.

¹⁴ NOAA Climate.gov, *Understanding the Arctic Polar Vortex*, (March 2021).

Electricity Markets

Electric Capacity

Figure 3: Planned and Actual Capacity Additions and Retirements



Source: EIA 860M, September 2021 Release. Expected and Actual Additions and Retirements from March 2021 through February 2022. Data exclude Alaska and Hawaii.

Preliminary data from EIA¹⁵ indicates that from March 2021 through February 2022, electric net winter capacity additions are expected to total approximately 42.4 GW and electric net winter capacity retirements are expected to total over 7.6 GW.¹⁶ As shown in Figure 3, the majority of the electric net winter capacity additions are expected to come from solar and wind resources.¹⁷ Solar resources are expected to make up 39% or 16.3 GW of the capacity additions, 140% higher than the 5-year average (6.8 GW). ERCOT leads Regional Transmission Organizations (RTOs) and Independent System Operators (ISOs) in overall capacity additions with 14 GW, including 6.8 GW of wind capacity additions. Notably, SPP has projected approximately 3.2 GW of wind capacity additions, which account for 98% of SPP’s total electric capacity additions. Similarly, MISO anticipates 2.1 GW of wind capacity additions, which make up 49%

of MISO’s total electric capacity additions. ISO-NE expects less than 1 GW of capacity additions, with 0.6 GW coming from solar capacity. In NYISO, the Indian Point 3 nuclear power unit, which provided over 1 GW of net winter capacity, retired in April 2021. In PJM, notable retirements include the June 2021 retirement of the Chalk Point coal plant, which provided over 0.7 GW of net winter capacity. In MISO, a total of 2.9 GW of coal net winter capacity are expected to retire through February 2022, including the 0.6 GW Dolet Hills coal plant in Louisiana and the R M Schahfer coal-fired units in Indiana with a combined 0.9 GW in

¹⁵ The EIA 860M data is as of release date September 2021. Figure 3 captures data on Operating and Standby resources entering operation and expected capacity retirements during the months of March 2021 through February 2022. Figure 4 captures Operating and Standby resources expected to be available through October 2021. It also captures expected capacity retirements and planned capacity through October 2021.

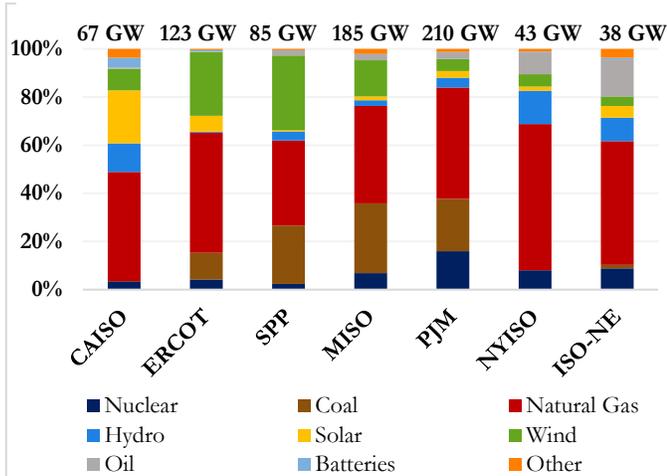
¹⁶ In this section, capacity refers to net winter as defined by the EIA as the maximum output, commonly expressed in MW, that generating equipment can supply to system load, as demonstrated by a multi-hour test, at the time of peak winter demand (period of December 1 through February 28).

¹⁷ As illustrated in Figure 3, the electric capacity retirements taking place during the winter are nuclear and coal resources—resources with higher capacity factors. The majority of the electric capacity additions are solar, wind, and battery resources—resources with lower capacity factors.

generating capacity. From March 2021 through February 2022, coal retirements are expected to total 5.1 GW, 41% lower than the total coal retirements last year (8.7 GW).

As shown in Figure 4, across all RTOs/ISOs, natural gas is expected to provide roughly 45% of the net winter capacity, followed by coal, wind, and nuclear.

Figure 4: Expected Capacity Mix by RTO/ISO



Source: EIA 860M, September 2021 Release. Expected Capacity Mix through October 2021.

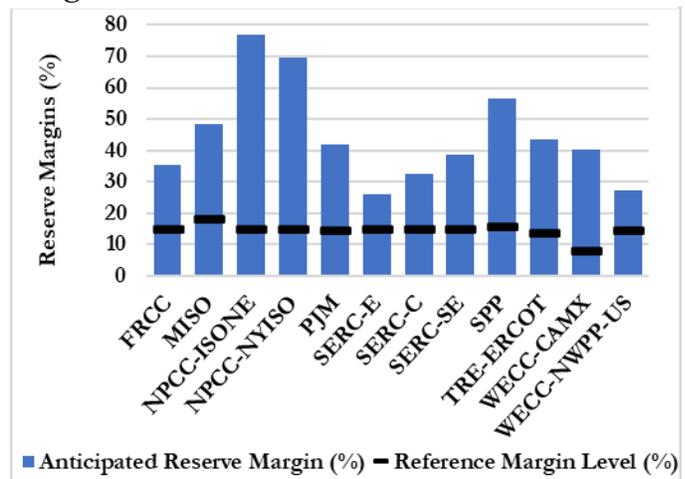
In NYISO, installed natural gas generators will account for 61% of the total capacity. Natural gas generators are expected to provide 51% of total capacity in ISO-NE and 46% in PJM. ERCOT is expected to have the largest amount of installed wind capacity at 32.6 GW or 27% of total ERCOT capacity by October 2021, and SPP expects to have the largest percentage of installed wind capacity, with 26.5 GW of wind capacity or 31% of total SPP capacity. Installed wind capacity will provide 15% of total capacity in MISO. Variable resources, such as wind and solar, have seen an increase in generation share since 2006. The installed wind generation capacity has increased from 1% of total capacity across all RTOs/ISOs, in 2006, to the expected 14% or 108 GW by October 2021. During the same period, coal resources have retired at an average of 4.4 GW per year, with a steady decline in the percentage of installed generation capacity from 29% to 18%.

Reserve Margins

NERC Regional Entities’ and RTOs/ISOs’ data indicate that planning reserve margins – the available electric generation capacity in excess of expected peak electricity demand – should be adequate this winter for all regions. The blue columns shown in Figure 5 display the anticipated reserve margins for the markets and regions, while the black bars indicate the reference reserve margin each region aims to exceed. The lowest reserve margin is expected in SERC-East (SERC-E, North and South Carolina), although its expected reserves of 26% are still expected to exceed NERC’s reference margin level of 15%.

Although all regions are expected to maintain adequate reserve margins through the winter, reserve margins are not guarantors of reliable operations. A variety of factors affect reliable operations and have to be managed by transmission operators to help maintain electric supply and reliability. For instance, fuel availability, particularly natural gas and fuel oil, can affect generator availability and has to be monitored by transmission operators. Additionally, expected demand for coal

Figure 5: NERC 2021 Anticipated Reserve Margins



Source: North American Electric Reliability Corp.

generation could face constraints on deliveries from mines, and due to rail and truck performance, which would result in larger draws from stockpiles.¹⁸ In response, RTOs are monitoring fuel availability. As an example, PJM now requires weekly coal and oil fuel inventory reports for each generating unit. These reports will continue through February 28, 2022. Also, transmission operators have to accurately forecast solar and wind generation and take forecasted generation into account when managing the intra-day and intra-hour transitions between higher and lower variable resource availability. One of the key recommendations from the Joint Inquiry is that Planning Coordinators¹⁹ should reconsider some of the inputs, including adjusting load forecasting, assessing wind capacity contributions, excluding or derating gas capacity with non-firm supply, and including sub-zone analysis for regions with wide geographic footprints, to their publicly-reported winter season anticipated reserve margin calculations for their respective Balancing Authority footprints so that the reported reserve margins will better reflect the reserve levels that the Balancing Authorities could experience during winter peak conditions. As such, the recommended improvements should result in seasonal reserve margin projections that better account for resource and demand uncertainties and better align with each Balancing Authority's footprint's near-term planning during forecast cold weather events.²⁰

Resource Adequacy

After facing resource shortages during the February 2021 winter storm, a number of regions have evaluated their planning processes and winter preparedness measures, including enhancements to resource adequacy programs, to identify potential improvements based on what they have learned from the event.

To ensure sufficient capacity from generation and other resources to support electric reliability and market operations, RTOs/ISOs and other regional organizations rely on capacity markets or other resource adequacy constructs to procure and compensate needed resources. Several markets identified needed improvements to their resource adequacy constructs through stakeholder processes or a review of prior events, and some implemented changes that will be in effect this winter.

Both SPP and MISO noted that the availability of fuel for generators was critical to electric system reliability in the February 2021 event and as a result they are examining policies to improve resource adequacy and fuel supply and deliverability. In light of the February 2021 winter storm event, SPP and its stakeholders have begun exploring ways to ensure resource availability during the winter months, potentially including improvements to SPP's resource adequacy construct.²¹ SPP staff are currently working to examine this issue,

¹⁸ IHS Markit. *Coal & Energy Market Commentary* (September 27, 2021).

¹⁹ Planning Coordinators are the NERC certified and responsible entity that coordinates and integrates transmission Facilities and service plans, resource plans, and Protection Systems. See NERC, *Glossary of Terms Used in NERC Reliability Standards*, (June 2021).

²⁰ FERC, NERC, *February 2021 Cold Weather Grid Operations: Preliminary Findings and Recommendations Presentation*, (September 23, 2021), Slide 24.

²¹ SPP, *A Comprehensive Review of Southwest Power Pool's Response to the February 2021 Winter Storm: Analysis and Recommendations*, July 19, 2021.

among others, at the direction of SPP’s board of directors.²² In neighboring MISO, the Resource Availability and Need (RAN) initiative is continuing to work on improvements, including improved accreditation of resources and a seasonal resource adequacy requirement.²³

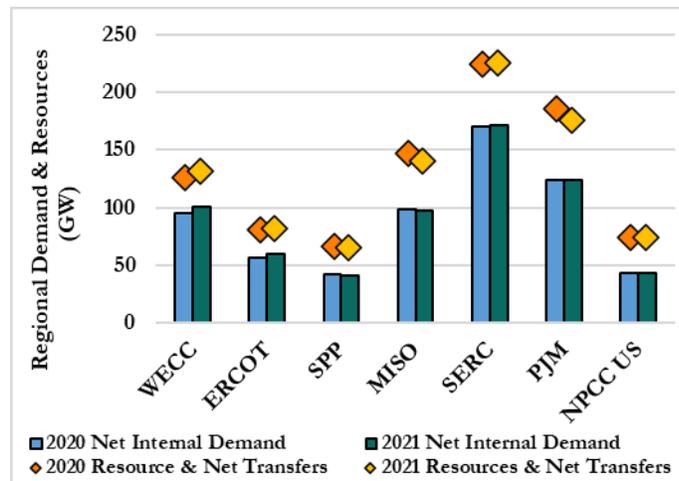
The Northwest, a winter-peaking region, relies heavily on hydroelectric generation to serve load. Recent hydropower production levels varied across the Northwest, as much of the region experienced drought conditions this year.²⁴ Although entities in the Northwest have historically performed resource adequacy planning and procurement on an individual basis, NWPP is currently developing a regional resource adequacy program (NWPP RA program) to augment the resource planning that individual utilities conduct. The NWPP RA program will remain voluntary and non-binding during the winter 2021-2022 months.²⁵

Peak Load Forecasts and Net Transfers

NERC forecasts net demand for electricity will increase by approximately 1% for winter 2021-2022 when compared to winter 2020-2021 levels, with a slight increase in demand concentrated in the SERC-Florida subregion, ERCOT, and the WECC-NWPP subregion, and a decrease in demand in MISO and the SERC-East subregion. For the remaining regions and subregions, NERC forecasts demand will remain similar to winter 2020-2021 levels.

Figure 6 illustrates demand growth compared to the previous winter, highlighting that NERC anticipates that each region will have enough resources and net transfers available to exceed their net internal demand.

Figure 6: Winter Regional Demand and Resources



Source: North American Electric Reliability Corp.

Nationally, NERC forecasts a decrease of 11 GW in combined available resources and net transfers between regions from 906 GW in winter 2020-2021 to 895 GW in winter 2021-2022, and a 7 GW increase in regional internal demand, net of demand response, from 630 GW in winter 2020-2021 to 637 GW in winter 2021-2022. Overall, these projections were calculated with

²² SPP, *SPP Board Directs Action on Winter Storm Recommendations*, (July 27, 2021).

²³ MISO, *Resource Adequacy Reforms Conceptual Design*, (August 16, 2021).

²⁴ Utility Dive, *Historic Drought Slashes Hydropower Generation in California, Other Western States*, (August 24, 2021). <https://www.utilitydive.com/news/historic-drought-slashes-hydropower-generation-in-california-other-western/605421/>

²⁵ Northwest PowerPool, *NWPP Resource Adequacy Program – Detailed Design*, (August 30, 2021).

preliminary data from the RTOs/ISOs and NERC Regions for NERC's upcoming 2021 Long Term Reliability Assessment.

Natural Gas Markets

Natural Gas Prices

This section analyzes the year-over-year futures price changes this winter at major U.S. natural gas hubs, then discusses the regional market conditions and the state of the natural gas transportation infrastructure connecting them. As seen in Figure 7, as of October 13, 2021, futures prices for natural gas this winter (November 2021 through February 2022)²⁶ exceed the final settled futures prices for the last two winters across a sample of ten major natural gas hubs comprising the national benchmark Henry Hub in Louisiana and nine other major supply and demand hubs in the Lower 48 States. As of October 13, 2021, the Henry Hub futures contract price, the base component of winter futures prices for all trading locations,²⁷ is up 103% from last winter's settled price, increasing \$2.85/MMBtu (the lowest expected year-over-year price increase in Figure 7) to \$5.63/MMBtu for winter 2021-2022.

According to EIA, rising domestic natural gas consumption for sectors other than electric power, relatively minor natural gas production growth, and continued growth in LNG exports has driven up Henry Hub spot prices over the course of the year and the same factors, while lessened, are still expected to carry momentum in rising prices over the winter. The winter outlook for each of these fundamentals is covered in detail later in this report.

While domestic fundamentals are the main drivers of U.S. natural gas prices, international markets are also expected to affect U.S. natural gas markets and prices this year. Over the last decade, the development of LNG has transformed what were once many disparate regional markets into an integrated global market. The U.S. participates in the global market by importing and exporting natural gas via pipeline throughout North America, supplying demand for feedgas at LNG export terminals, and through LNG import demand, primarily in the New England market. As discussed later in this report, U.S. LNG export demand is expected to be high this winter due to strong expected profits for exporting to both Asian and European markets, but U.S. LNG export capacity is expected to be limited to up to 12.3 Bcfd. Global LNG prices grew rapidly over the course of the summer as demand from major import markets in Asia recovered from COVID-19 pandemic-induced lows, with China reportedly increasing imports by 30% over pre-pandemic levels.²⁸

²⁶ Natural gas futures prices are price quotations in futures contracts for the exchange of natural gas, as either a physical or financial settlement, at a specified time in the future. Winter futures prices in this section are the average quotes of the last traded futures contracts, as of October 13, 2021, for the winter months, e.g., November 2021, December 2021, January 2022, and February 2022 strips.

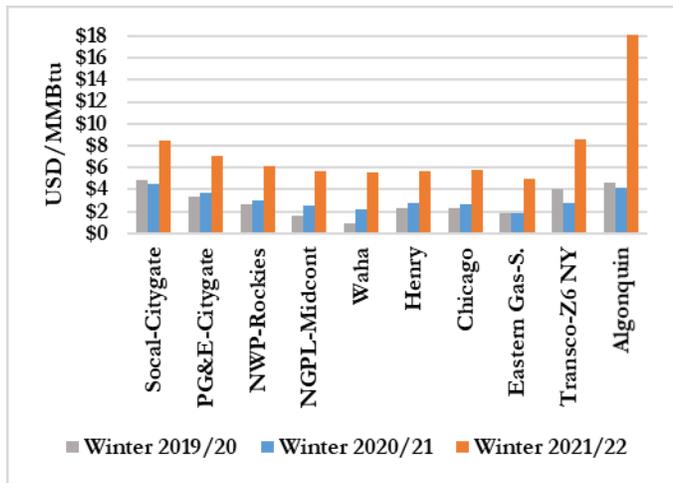
²⁷ Regional natural gas prices are calculated by adding the Henry Hub winter futures price to the winter basis futures prices at major trading hubs in the U.S. Regional basis prices reflect, among other things, the distance from producing basins, availability of natural gas transportation, and local weather expectations for the coming winter.

²⁸ The Oxford Institute for Energy Studies, *Why Are Gas Prices So High?* (September 2021).

Regional fundamentals in Europe, another major demand market for LNG, have also played a part, as natural gas prices in Europe reached all-time highs this summer and remain high heading into the winter. According to RBN Energy, higher natural gas prices in Europe are likely this winter as European natural gas storage inventory is at the lowest level for a September in recent history.²⁹ Also, Europe is experiencing a tight supply and demand balance, brought on by continuing declines in domestic natural gas production, decreased imports from Russia, and power sector fundamentals that have slowed switching to other energy sources for electric generation.³⁰ As a result, high global LNG prices are likely to persist, which will likely incentivize high LNG export demand while also supporting higher peak natural gas prices in New England as that regional natural gas market will likely partially rely on imported LNG in the winter.

Higher peak natural gas prices in New England are reflected in Algonquin Citygate futures. Algonquin Citygate, outside Boston, has the largest expected year-over-year futures price increase, at \$13.98/MMBtu, where futures prices more than quadrupled (from \$4.20/MMBtu for winter 2020-2021, to \$18.18/MMBtu

Figure 7: Average U.S. Natural Gas Futures Prices Across Major Hubs for November to -February



Source: InterContinental Exchange Inc.

for winter 2021-2022). While Algonquin Citygate prices are often discounted to Henry Hub most of the year, Algonquin Citygate prices typically increase above Henry Hub prices in January and February due to the winter-peaking New England region’s limited natural gas pipeline capacity. LNG import terminals in the area can dull the impact of rising prices, but with European LNG prices trading around \$32/MMBtu this winter (as of October 13, 2021), New England futures prices are rising alongside European LNG prices in order to compete for global LNG cargoes. While the average futures price for the entire winter 2021-2022 strip for the Algonquin Citygate hub is \$18.18, January and February 2022 prices, in particular, have risen well above the rest of the winter strip and are trading above \$21.00/MMBtu, as of October 13, 2021.

Several major demand hubs are anticipating large rises in year-over-year futures prices for winter 2021-2022, with at least a 100% price increase expected at major hubs in the East, and at least an 87% price increase at major demand hubs in Chicago and California. More specifically, winter 2021-2022 futures for the Chicago Citygate hub are trading at \$5.80/MMBtu, and Transco Z6 (NY), a major hub outside New York City, is trading at \$8.63/MMBtu.

Similarly, supply hubs are also expecting increases in year-over-year futures prices for winter 2021-2022. For example, at the Permian Basin’s Waha trading hub, located in West Texas, futures prices have climbed to \$5.51/MMBtu, increasing above Appalachia’s Eastern Gas South hub, located in western Pennsylvania at the

²⁹ RBN Energy, *It's Too Late - Global Natural Gas/LNG Supply Squeeze Sets Stage for Record Winter Prices*, (September 10, 2021).

³⁰ The Oxford Institute for Energy Studies, *Why Are Gas Prices So High?* (September 2021).

center of the Marcellus Shale, where prices rose to \$5.03/MMBtu. NWP-Rockies, a major hub in the Rockies, similarly saw futures prices rise to \$6.11/MMBtu, up \$3.07/MMBtu from last winter.

Until last year, the West Texas Permian Basin region typically experienced relatively low natural gas prices at the Waha hub due to capacity constraints as natural gas production often exceeded regional takeaway pipeline capacity. However, new takeaway capacity from the Permian basin³¹ and this year's economic rebound from the initial impact of the COVID-19 pandemic have provided upward price pressure. Furthermore, the new takeaway capacity from the Permian basin increasingly interconnects several major natural gas hubs in Texas,³² reflecting a higher level of correlation between the forward prices for the West Texas markets and the South Texas/Gulf Coast markets. As a result of these factors, the average Waha basis has narrowed significantly from -\$0.56/MMBtu in winter 2020-2021 to -\$0.12/MMBtu in winter 2021-2022.

In California, PG&E Citygate, a major hub in northern California, has seen winter 2021-2022 futures prices rise to \$7.06/MMBtu. This futures price increase reflects increases in the Winter Strip forward price at the Rockies and the Permian regions, which both serve PG&E. Winter 2021-22 futures prices at the Southern California Citygate (SoCal-Citygate) hub, near Los Angeles, have risen to \$8.48/MMBtu, due to the continued restrictions on working gas capacity at the Aliso Canyon storage facility. Working gas capacity restrictions have limited capacity to 34 Bcf, compared to the designed storage capacity of 84 Bcf. The Aliso Canyon capacity restrictions, coupled with the increase in Permian and Rockies Winter Strip prices over last winter, have led to the increased futures prices for this winter.

Southern California Gas Company (SoCalGas) announced unplanned maintenance for safety testing on its Line 3000 that will restrict receipt capacity on its system from September 11 through December 31, 2021. This could place more upward pressure on prices at the SoCal Citygate and SoCal Border hubs, located at the California and Arizona border, during cold weather events in the early winter. The Winter Forward Strips at these two hubs were higher than last winter's strips before the maintenance was announced and have risen considerably since the announcement.

Natural Gas Production

U.S. natural gas production is expected to increase this winter compared to last winter. The EIA forecasts dry natural gas production to average 94 Bcfd in winter 2021-2022, increasing nearly 4%, or 3.2 Bcfd, from average winter 2020-2021 production levels of 90.8 Bcfd, as shown in Figure 8. The forecasted increase in natural gas production marks a return to the growth trend observed over the last decade after winter production declined in winter 2020-2021, but is likely to remain below the levels seen in winter 2019-2020. Natural gas production had experienced a 12% year-over-year increase in winter 2018-2019 and a 7% year-over-year increase in winter 2019-2020, before decreasing 6% in winter 2020-2021 as the natural gas market reacted to the COVID-19 pandemic. Over the last year, natural gas producers cited the need to reduce production expenditures in response to lower natural gas prices in order to prioritize shareholder returns over

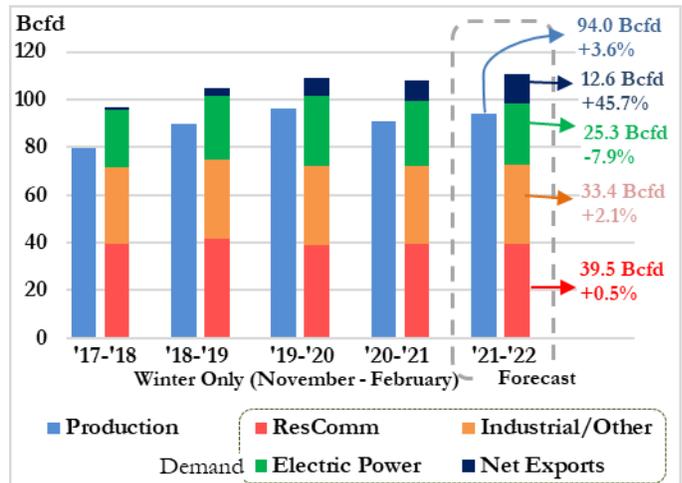
³¹ Two intrastate pipelines – the Permian Highway and Whistler pipelines – are adding 4.1 Bcfd of takeaway capacity from the Permian Basin, located in west Texas and eastern New Mexico, to the Gulf Coast and have supported a strong recovery in Waha hub prices.

³² Including the Waha hub in the Permian producing basin, Agua Dulce in South Texas, the Katy hub near Houston, and the Houston Ship Channel (HSC), a major downstream demand market.

the long-term.³³ In addition, while drilling activity has increased in response to higher oil and natural gas prices, the time lag for drilling activity to translate into production could keep production limited and natural gas prices higher this winter.³⁴ Natural gas producers are expected to modestly increase production levels this winter, following rising natural gas prices.

In regard to production regions, the Marcellus and Permian basins, both shale formations, represented the largest shares of domestic natural gas production with 27% and 13%, respectively, in 2021 through July. Moreover, the Marcellus and Permian Basins have also strongly contributed to natural gas production growth. The Marcellus Basin increased its average natural gas production by 1.5 Bcfd in 2021 through July compared to the same period in 2020. Similarly, the Permian Basin increased its average natural gas production by roughly 0.8 Bcfd in 2021 through July compared to the same period in 2020.

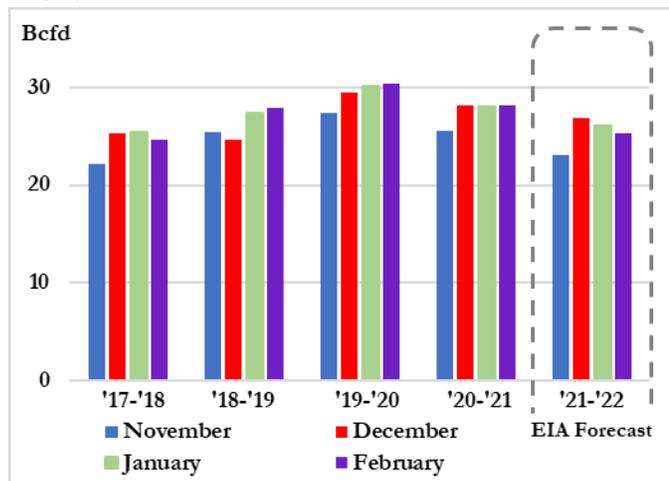
Figure 8: Winter Natural Gas Production and Demand



Source: EIA

Natural Gas Demand

Figure 9: Winter Natural Gas for Power Burn by Month



Source: EIA

The EIA forecasts overall natural gas demand to increase to 111 Bcfd for winter 2021-2022, a 2.5% increase, despite decreasing demand for electric power generation (see Figure 8 above). This forecast contrasts with the slight decline in total natural gas demand observed last winter due to milder weather and the effects of the COVID-19 pandemic. Even though natural gas demand growth this winter is expected to be slightly below production growth, some sectors of demand, such as exports, are placing high pressure on prices, as noted above. In particular, expected year-over-year demand growth is largely driven by an increase in net exports. Winter net exports, calculated as total natural gas exports minus imports, have remained positive since the winter of 2017-2018 due to the expansion of LNG exports. This winter, net exports are expected to increase 46%, to nearly 12.6 Bcfd. LNG gross exports, the largest portion of net exports, are expected to increase 21%, to 11 Bcfd. Increasing winter LNG exports are driven largely by increased global

³³ See e.g. BTU Analytics, *Will Recent E&P Capital Discipline Impede a Production Recovery?*, (May 2021).

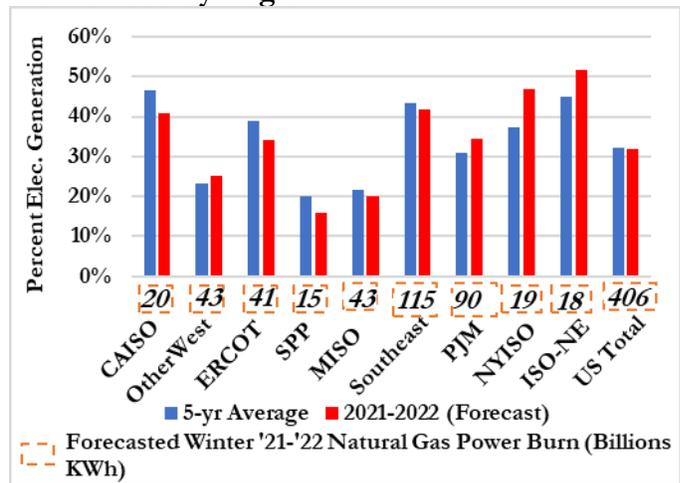
³⁴ IHS Markit, *North American Natural Gas Short-Term Outlook*, (September 2021).

demand for natural gas, making it profitable to export LNG. A more detailed discussion regarding natural gas imports and exports is contained in the following section. Furthermore, the EIA forecasts increases in demand for natural gas in the residential and commercial demand and industrial/other demand sectors over last winter, with the residential and commercial demand sectors increasing by less than 1.0% to 39.5 Bcfd, and the industrial and other sectors increasing 2% to just over 33 Bcfd.

Despite the forecast of increasing total demand for natural gas this winter, natural gas consumption by the electric power sector for the generation of electricity is forecast to average 25.3 Bcfd (23% of natural gas demand expected this winter), 8% below levels observed last winter, as shown in Figure 9. The decline in power burn is largely driven by an increase in the price of natural gas across the country, causing some substitution to generation fired by other fuels, such as coal.

As reflected in the declining use of natural gas for power burn, the share of electricity generated from natural gas in the U.S. is expected to decline close to two percentage points from the 34% observed last winter to 32%. In particular, the share of electricity generated from natural gas is expected to decline in CAISO, ERCOT, SPP, MISO, and the Southeast relative to their respective five-year averages, while ISO-NE, NYISO, PJM, and other western regions are expecting an above average share of generation output from natural gas, as shown in Figure 10. For ISO-NE, natural gas share of generation output is expected to be at 52% this winter (with a five-year average of 45%). For PJM this share is expected to be at 34% (with a five-year average of 31%) and for NYISO this share is expected to be at 47% (with a five-year average of 37%). This winter's share of electricity generated from natural gas in the U.S. will be approximately equal to the five-year average of 32%, but below the previous winter's share, as noted above. Increases in the share of generation from other resources will make up for reductions in generation from natural gas, with renewable generation expected to increase its share of generation by almost 1.6 percentage points, and coal expected to increase its share of generation output by about one percentage point. Constraints on these other energy sources, including coal availability, could result in higher than expected natural gas demand for power burn.

Figure 10: Share of Generation Output from Natural Gas by Region



Source: EIA

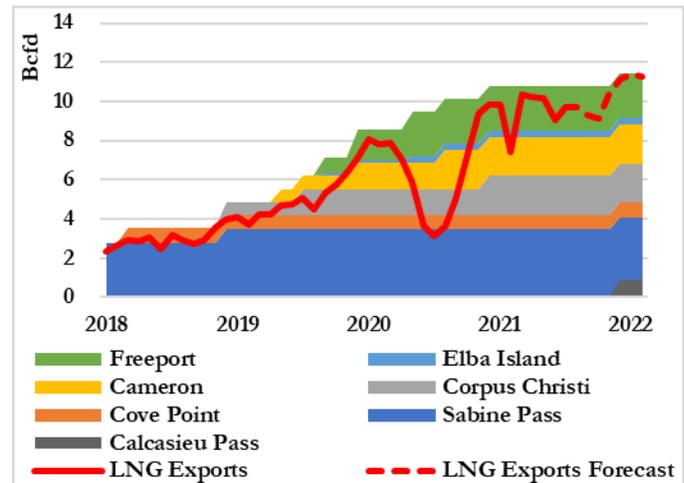
Natural Gas Exports and Imports

Exports of natural gas are expected to increase during winter 2021-2022. In particular, the EIA expects LNG exports to increase above winter 2020-2021 levels due to increased U.S. liquefaction capacity and expected international demand. The EIA forecasts U.S. LNG gross exports to average 11 Bcfd between November 2021 and February 2022, a 21% increase from the average in winter 2020-2021. In addition, pipeline gross exports are expected to see year-over-year growth, averaging 9.3 Bcfd, up 15% from last winter. U.S. LNG export capacity is expected to increase by almost 1.5 Bcfd between March 2021 and February 2022. Notably, Sabine Pass, located in Louisiana, plans to place its sixth liquefaction train into service in December 2021, adding 0.6 Bcfd in export capacity. Similarly, Calcasieu Pass, also in Louisiana, plans to begin operations with 0.9 Bcfd in export capacity as early as December 2021. U.S. LNG export facility utilization remained high for

most of winter 2020-2021, aside from February 2021 when high prices and production freeze-offs associated with the February 2021 winter storm resulted in temporary curtailments at some facilities. Figure 13 shows total U.S. LNG exports, forecasted U.S. LNG exports, and maximum export capacity by terminal.

As mentioned in the Natural Gas Prices section above, increased international LNG demand has increased international prices and continued to incentivize high U.S. LNG exports. East Asian countries, particularly China, Japan, South Korea, and Taiwan, have driven much of the increase in LNG export demand.³⁵ For its part, the U.S. has exported 738 Bcf, or 36% of total 2021 U.S. LNG exports through July 2021, to South Korea, China, and Japan. In addition to increased international LNG demand, international LNG export capacity from other countries has decreased due to outages, such as the outage at Norway's Hammerfest plant resulting from a fire in September, and feedgas supply issues impacting Trinidad and Tobago, and Nigeria. The decreased international LNG supply has tightened the international LNG market and

Figure 11: U.S. LNG Capacity and Feedgas Demand



Source: EIA

increased international LNG prices which, in turn, will likely incentivize high utilization rates from U.S. LNG export terminals throughout the winter. Furthermore, natural gas imports, both from LNG import terminals and natural gas pipelines entering the U.S. from Canada, also play a valuable role in balancing the natural gas markets during the winter months. Last winter, LNG imports averaged 0.2 Bcf/d while gross pipeline imports averaged 8.4 Bcf/d. The EIA expects natural gas imports to help balance the Northeast markets in winter 2021-2022 with gross LNG imports for the entire country averaging 0.3 Bcf/d, a 93% year-over-year increase, while forecasting gross pipeline imports to fall 12% year-over-year to average 7.4 Bcf/d. LNG imports supplying New England limit the impact of pipeline capacity constraints in the region. These LNG imports include the Everett LNG terminal and the Northeast Gateway facility, both in Massachusetts, and the Canaport facility, located just north of the U.S.-Canadian border in New Brunswick. High expected natural gas prices in New England this winter could incentivize more imports into the region. Moreover, several expansion projects in western Canada could increase total import capacity into the U.S. Pacific Northwest, where imports compete with production from U.S. production centers such as the Rockies.

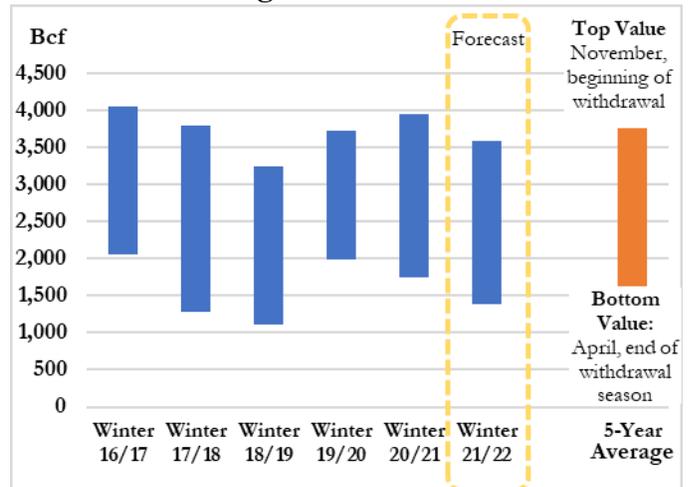
Natural Gas and Propane Storage Inventories

Going into this winter, forecasts predict storage inventory levels below the five-year average, both for natural gas and propane. Natural gas storage inventories are forecast to begin the winter 2021-2022 withdrawal season, which generally runs from November to April, at 3,572 Bcf, 5% below the five-year average, as shown in Figure 14. The low inventory forecast for the start of the withdrawal season ties to a lower-than-average injection season, which generally runs from April to October, coupled with record storage withdrawals during the February 2021 winter storm. Storage inventories began the 2021 injection season this March at 1,750 Bcf,

³⁵ The Oxford Institute for Energy Studies, *Why Are Gas Prices So High?* (September 2021).

12% lower than the start of the 2020 injection season (1,986 Bcf) and 2% lower than the five-year average of the starting inventory for the injection season (1,778 Bcf). The total volume of natural gas injection expected in 2021 is 1,822 Bcf, 8% below the five-year average for injections (1,977 Bcf), and the third lowest in the past five years. This lower-than-average injection volume is expected due to tight supply and demand balances for natural gas this summer as a result of increased natural gas exports and record power burn in June 2021 due to hot weather. Moreover, withdrawals for the upcoming winter 2021-2022 are expected to be 2,085 Bcf, only 1.6% below the five-year average (2,120 Bcf). At the end of the withdrawal season, natural gas storage inventories are forecast to reach 1,486 Bcf, 9% below the five-year average (1,635 Bcf) due to a combination of lower than average inventory at the start of the withdrawal season and only a minor reduction in withdrawals from the 5-year average expected this winter.

Figure 12: U.S. Seasonal Change in Lower 48 Natural Gas Storage Inventories



Source: EIA

Propane, an alternate form of winter heating fuel,³⁶ will also start this winter with stock levels below the five-year average. Propane stocks for the first week of October are at 72.3 million barrels, 20% below the five-year average for the same week (90.5 million barrels) and the lowest level in the past five years for the same week. In order for propane storage levels to match the five-year average for the start of winter, an additional 16.4 million barrels of propane would need to be added to storage through the end of October. Propane stocks have been trailing below the past five-year range (Jan 2016 – Dec 2020) most of this year and will likely continue under the range all winter long.

Considerations for the Upcoming Winter

This section of the report highlights several notable issues for consideration as entities prepare for the upcoming winter. Specifically, this section highlights three issues: winter readiness recommendations from the Joint Inquiry; natural gas dependence in New England; and interregional transfer capacity.

Winter Readiness

Adequate winterization and other seasonal preparations by Generator Owners, Generator Operators, and Balancing Authorities, as well as natural gas infrastructure operators will be essential to ensuring that generation, transmission, and fuel infrastructure are operational during winter storms and extreme cold.

Since 2010, FERC and NERC have issued a number of reports emphasizing the importance of winterization and other seasonal preparations to ensuring reliability of the electric grid during extreme cold and severe

³⁶ Propane is also used in agricultural production to dry grain. According to the EIA, higher petrochemical demand for propane is expected to outweigh lower demand for grain drying and space heating this winter.

weather events. Most recently the 2021 Joint Inquiry's presentation,³⁷ proposed a number of preliminary recommendations for future winters. These recommendations are in addition to the existing winter readiness recommendations outlined in the 2019 FERC and NERC Staff Report on the January 17, 2018 cold weather bulk power system event³⁸ and the NERC guideline for generating unit winter readiness,³⁹ which continue to be relevant for bulk power entities. These recommendations include:

- Generator Owners are to identify and protect cold-weather-critical components and systems for each generating unit. Cold-weather-critical components and systems are those which are susceptible to freezing or otherwise failing due to cold weather, and which could cause the unit to trip, derate, or fail to start. (Implementation Timeframe before Winter 2023/2024)
- Generator Owners are to design new or retrofit existing generating units to operate to a specified ambient temperature and weather conditions (e.g., wind, freezing precipitation). The specified ambient temperature and weather conditions should be based on available extreme temperature and weather data for the generating unit's location, and account for the effects of precipitation and accelerated cooling effect of wind. (Implementation Timeframe before Winter 2023/2024)
- Generator Owners and Generator Operators are to conduct annual unit-specific cold weather preparedness plan training. (Implementation Timeframe before Winter 2022/2023)
- Generator Owners that experience outages, failures to start, or derates due to freezing are to review the generating unit's outage, failure to start, or derate and develop and implement a corrective action plan for the identified equipment, and evaluate whether the plan applies to similar equipment for its other generating units. (Implementation Timeframe before Winter 2022/2023)

Whether and to what extent entities implement these recommendations may have a significant impact on bulk-power system performance this winter.

Natural Gas Dependence in New England

Fuel availability for power generation is a primary concern when assessing winter readiness and electric reliability efforts, particularly for generators using natural gas and liquid fuels (e.g., oil, diesel, liquid petroleum gas).⁴⁰ This is particularly important in ISO-NE and NYISO, where natural gas is expected to account for approximately 52% and 47% of the regions' electric generation energy output, respectively (see Natural Gas Demand (power burn) above). These regions are also prone to severe winter weather conditions that place them at risk of experiencing generator fuel shortages during prolonged periods of extreme cold weather. This

³⁷ FERC, NERC, *February 2021 Cold Weather Grid Operations: Preliminary Findings and Recommendations Presentation*, (September 23, 2021).

³⁸ Federal Energy Regulatory Commission, *The South Central United States Cold Weather Bulk Electric System Event of January 17, 2018*, (July 2019).

³⁹ North American Electric Reliability Corp., *Reliability Guideline on Generating Unit Winter Weather Readiness – Version 3*.

⁴⁰ NERC, *2021 ERO Reliability Risk Priorities Report*, (August 12, 2021).

occurred most recently in the winter 2017-2018 when New England experienced a deep freeze and natural gas supplies become scarce, causing the electric system to experience significant operational and market stress.

Natural gas availability is more of a concern in New England due to the size of New England's peak winter natural gas demand combined with the limited number of pipelines and available pipeline capacity into the region. New England has no internal production of natural gas and a negligible amount of local natural gas storage capacity. New England is served by three major natural gas importing pipelines, however, despite a few expansions, this capacity has remained largely unchanged for decades. The vulnerabilities in New England can be particularly acute when natural gas-fired generators compete for pipeline capacity with the natural gas local distribution companies (LDCs). The LDCs have long-term contracts for firm transmission service for delivery of natural gas enabling them to supply natural gas to local customers during such weather events.⁴¹ This is in contrast to some natural gas-fired generators in the region, which historically have not contracted for long-term firm pipeline capacity,⁴² limiting their ability to secure and transport natural gas to their facilities during extreme cold weather events.⁴³ ISO-NE has relied on oil-based dual-fuel generation when extreme cold weather events have occurred, which is typically more expensive than natural gas-fired generation. Additionally, these events can present a significant risk because there is limited on-site fuel oil storage capacity at the oil-based dual-fuel plants, causing the power grid to become severely stressed.⁴⁴

The New England LNG import terminals can provide some peak-shaving deliveries of imported LNG to the region; however, their capacity is limited and imported LNG is more expensive than pipeline natural gas deliveries. As noted above in the Natural Gas Prices and Exports and Imports sections, European LNG prices are trading as high as \$32/MMBtu this winter (as of September 27, 2021). New England natural gas forward prices (Algonquin Citygate hub) for January and February 2022 are trading above \$21.00/MMBtu (average of \$18.18/MMBtu for the entire winter 2021-2022), which suggests natural gas buyers are competing with the European market for LNG cargoes.

Very expensive LNG imports could lead to scarce natural gas supply in periods of peak demand, as has occurred in past winters in New England. During scarcity periods and extreme weather events in past winters, Algonquin Citygate's daily spot prices have briefly exceeded \$100/MMBtu. This winter, supply scarcity is likely to be more persistent, and the high winter futures prices of \$18.18/MMBtu at Algonquin Citygate hub are reflective of market participants' concerns. These high natural gas prices can also result in very high electricity prices, as ISO-NE has increasingly turned to natural gas-fired generation. While ISO-NE also has generation capacity with dual-fuel capability of switching to fuel oil when natural gas supply is too expensive or unavailable, fuel oil capacity is limited and some reports have indicated that on-site fuel stocks at dual-fuel generators are running below historic average inventories.⁴⁵ This increases the potential for scarcity conditions

⁴¹ ISO New England, *Operational Fuel-Security Analysis*, (January 17, 2018).

⁴² *Id.*

⁴³ ISO New England, *Natural Gas Infrastructure Constraints*, <https://www.iso-ne.com/about/what-we-do/in-depth/natural-gas-infrastructure-constraints>. (Accessed on October 4, 2021).

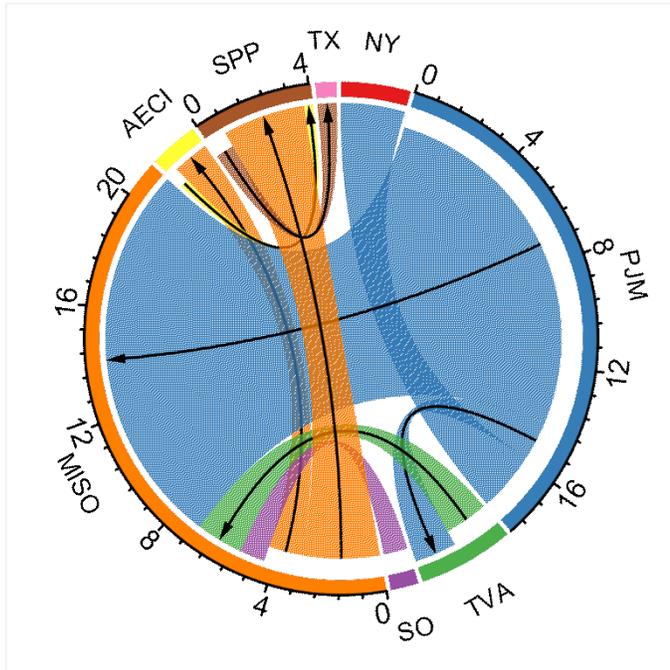
⁴⁴ ISO New England, *Operational Fuel-Security Analysis*, (January 17, 2018).

⁴⁵ S&P Global Platts, *ISO-NE Updates Power Generators Ahead of Winter Amid Supply Chain Constraints*, (October 1, 2021).

and sharply elevated power prices in ISO-NE. In extreme weather events, fuel scarcity could force some industrial and commercial users to curtail their activities and could result in outages in the natural gas and electric sectors.

Interregional Transfer Capacity

Figure 13: Balancing Authority Electricity Transfer from February 14 to 18, 2021, Average



Source: EIA-930 and staff analysis.

Note: Graph includes Balancing Authorities transferring more than 500 MW, on average, to at least one other Balancing Authority. NY represents NYISO, SO represents Southern Company, AECl represents Associated Electric Cooperative Incorporated, TX represents ERCOT.

February 14 through February 18 were dominated by PJM, with PJM acting as a major source of power to MISO, which in turn transferred electricity to SPP. Arrows indicate the direction of electricity transfers originating from PJM (shown in blue) through MISO, Tennessee Valley Authority (TVA), and Associated

As noted by the Joint Inquiry, having available interregional transfer capacity of electricity is critical to supporting neighboring regions during extreme weather events and can have a significant impact on both market and reliability outcomes during extreme cold and winter storms.

In the Eastern Interconnection, PJM's location and the large number of transmission interconnections with neighboring regions will allow PJM to assist those regions during the coming winter. Generally, PJM transfers power to MISO to the west and (to a lesser extent) NYISO to the north.⁴⁶ As an example of the importance of interregional transfer capacity, PJM's transmission interconnections enabled it to support MISO and SPP during the February 2021 winter storm (see February 2021 Winter Storm section above). From February 15 through February 17, PJM transfers to all other regions for the top 10 interchange hours averaged more than three times hourly average transfers from PJM in 2020.⁴⁷ Total transfers from PJM reached an all-time peak of 19.1 GW on February 15, hour 18.⁴⁸

Figure 15 illustrates that average GWs of electricity transfers, between Balancing Authorities from

⁴⁶ Monitoring Analytics, *2020 State of the Market Report for PJM Volume 2*, Table 9-3

⁴⁷ PJM, *Winter Operations of the PJM Grid: December 1, 2020-February 28, 2021*, presented to the PJM Operating Committee, April 8, 2021. Monitoring Analytics, *2020 State of the Market Report for PJM Volume 2*, Table 9-5 p. 410 March 11, 2021 (showing 48,092 GWh of gross transfers from PJM during the 8,784 hours in 2020.)

⁴⁸ PJM, *Winter Operations of the PJM Grid: December 1, 2020-February 28, 2021*, presented to the PJM Operating Committee, April 8, 2021.

Electric Cooperative Incorporated (AECI) (located between MISO and SPP, mostly in Missouri) that supported transfers going to SPP and ERCOT. The width of each connection between Balancing Authorities in Figure 15 indicates the magnitude of electricity transferred, in GW at the outside of the circle.

Elsewhere in the Eastern Interconnection, operational studies from winter 2020-2021 show a potential for more than 7.5 GW of transfer capacity into NYISO from neighboring regions.⁴⁹ ISO-NE is slightly more electrically and geographically isolated than NYISO. Total transfer capacity potential into ISO-NE from New York and Canada is slightly greater than 45 GW.⁵⁰

As a benefit of interregional transfer capacity, prevailing flows can be reversed when needed during severe weather events. For example, even though SPP typically transfers power to MISO, MISO transferred critical electricity to SPP during the February 2021 winter storm. Overall, SPP has 6 GW of alternating current (AC) interties with MISO to the east, 1.5 GW of AC interties with the Southwestern Power Administration (SPA) in Arkansas, Missouri, and Oklahoma, over 5 GW of AC interties with the AECI in Oklahoma and Missouri, and over 1 GW of direct current (DC) interties to the Western Interconnection.⁵¹ In the Western Interconnection, CAISO has strong integration with neighboring Balancing Authorities, including members of its EIM, which had an average of 10 GW of EIM transfer capacity into CAISO in 2020, in addition to California Public Utility Commission's Resource Adequacy program transfers.⁵² Conversely, CAISO can provide 7.6 GW of EIM transfer capacity to neighboring Balancing Authorities participating in the EIM. There are additional, strong connections between EIM participants in the West, with Arizona Public Service able to provide over 7 GW of EIM transfers to the Salt River Project or transfer 4.7 GW from the Salt River Project. Similarly, Idaho Power is able to provide nearly 2 GW of transfers to PacifiCorp East and receive 1 GW of transfers from PacifiCorp East.⁵³ Notably, these figures do not include non-EIM transfers.

In contrast to other markets, ERCOT has limited transfer capability from two DC interties to SPP totaling a combined capacity of 820 MW, and 400 MW of capacity from two DC ties with Mexico.⁵⁴

Conclusion

The U.S. NOAA forecasts for November 2021 through February 2022 suggest above normal temperatures for most parts of the country, including New England, the Southeast, the Southwest, the Central U.S., the Rockies, and much of the Northwest and below normal temperatures for parts of the Midwest and the Pacific

⁴⁹ NYISO, *NYISO Operating Study Winter 2020-21*, Figure 2.

⁵⁰ ISO-NE Internal Market Monitor, *2020 Annual Markets Report*, Table 2-1 and Figure 2-20.

⁵¹ SPP MMU, *State of the Market Report 2020*, p. 10.

⁵² CAISO DMM, *2020 Annual Report on Market Issues and Performance*, Table 3.2.

⁵³ CAISO DMM, *2020 Annual Report on Market Issues and Performance*, Table 3.2.

⁵⁴ ERCOT, *ERCOT DC Tie Operations*, Figure 1.3.

Northwest. While NOAA predicts above average temperatures for much of the country, extreme cold and winter storms may still occur.

According to preliminary data from NERC, all planning regions should have enough electric capacity available to exceed their reserve margins this winter under expected conditions – with approximately 42.4 GW of electric capacity scheduled to enter operation and over 7.6 GW scheduled to retire from March 2021 through February 2022.

Overall, NERC forecasts an increase in net demand for electricity, and a decrease in combined available generation capacity and net transfers of electricity between regions. Higher than average temperatures throughout the U.S. might lower some of this demand, although this winter forecast does not foreclose the possibility of severe winter storms. Most of the scheduled new electric capacity consists of solar and wind resources while most of the scheduled retirements are coal and nuclear resources.

In the natural gas markets, winter 2021-2022 natural gas prices are expected to increase across the country due to rising exports and rising overall domestic demand with only modest increases in production. Due in part to rising natural gas prices, winter 2021-2022 natural gas production is expected to increase slightly above winter 2020-2021 levels. Also, due to this expected increase in natural gas prices, power burn is expected to decline. However, overall domestic demand for natural gas is expected to increase due to a rise in residential and commercial sector demand and industrial/other sector demand. Increases in the amount of generation output from other resources will likely make up for the projected reductions in electricity generated from natural gas. However, natural gas-fired plants may take on a larger role in electric generation output in regions in the West and the Northeast. The largest increase in natural gas demand is expected to come from a growth in net exports, from both LNG export facilities and pipeline exports. Increased LNG exports due to increased international demand are expected to be supported by new U.S. liquefaction capacity. Storage inventory levels going into this winter have fallen below the five-year average, both for natural gas and an alternate fuel for winter heating, propane.

In addition to driving greater demand for U.S. LNG exports, rising global LNG demand is expected to have a significant impact on the limited LNG import market in New England. U.S. LNG export facility utilization is expected to be high this winter due to strong expected profits for exporting to foreign markets. Global natural gas fundamentals in major demand markets for LNG, such as Asia and Europe, are leading to elevated prices worldwide. Natural gas prices in Europe reached all-time highs this summer and remain high as of publication. High global LNG prices are likely to persist into the northern hemisphere's winter, which has led to very high winter prices for the New England regional market, as it leans on LNG imports to meet peak season demand.

Finally, several issues are worth particular consideration for winter 2021-2022. Whether and to what extent entities implement the preliminary winter readiness recommendations from the Joint Inquiry and prior reports may have a significant impact on bulk-power system performance. Natural gas remains a critical fuel for reliability in New England. While LNG represents only a small amount of the region's natural gas import capability, the impact of rising global LNG demand could impact the system under tight conditions. Lastly, the importance of transfer capacity between regions may be critical to both reliability and economic outcomes during extreme cold weather.

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