How do we limit warming to 1.5°C: informing the Talanoa Dialogue question, "How do we get there?"

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This input unpacks key elements of the IPCC Special Report on Global Warming of 1.5°C relevant to the Talanoa Dialogue and the 1.5°C temperature limit in the Paris Agreement, focusing on the "How do we get there?" guiding question of the Dialogue. Climate Analytics provides a pool of information on science, impacts and risks of 1.5°C, the feasibility of holding warming below 1.5°C, necessary steps to limit warming to 1.5°C, and emissions reduction targets and 1.5°C pathways here: *http://climateanalytics.org/briefings/1-5c-key-facts.html*

Summary

This submission unpacks in some detail the implications of 1.5°C compatible mitigation pathways assessed in the IPCC Special Report on Global Warming of 1.5°C (IPCC SR1.5).[1] Integrated Assessment Models of climate change mitigation, assessed in IPCC SR1.5, show a large spectrum of 1.5°C-compatible pathways that limit warming to this level during the century, or exceed it by only a limited amount of less than 0.1°C ("low overshoot").

Where we are: The IPCC SR1.5 assesses the state of scientific knowledge on impacts of climate change, both currently experienced and likely to be felt in a future of 1.5°C warming or more, and related global greenhouse gas emission pathways. The report shows that we will be able to limit warming to 1.5°C, if the world takes further action substantially beyond what is implied by current Nationally Determined Contributions under the Paris Agreement (PA) in aggregate. However, any delay in near-term emissions reductions will lead to an increasing risk of greater temperature overshoot (with associated larger climate-change impacts and higher damages), a stronger reliance on uncertain mitigation options such as Carbon Dioxide Removal, and higher overall mitigation costs.

Where we want to go: The IPCC SR1.5 has assessed global greenhouse gas emission pathways that examine the technical and economic feasibility of limiting warming to 1.5°C. Simultaneously, the IPCC SR1.5 considers many dimensions of sustainable development that go beyond potential and actual impacts of climate change. The IPCC SR1.5 Summary for Policy Makers focuses on 1.5°C compatible mitigation pathways that limit global warming to 1.5°C, or below throughout the 21st century with no or limited (0.1°C) overshoot. These 1.5°C compatible pathways generally bring warming back to around 1.3°C warming by 2100 after a peak warming of 1.5°C or slightly above (less than 1.6°C) around the 2060s, and to achieve this have total greenhouse gas emissions peak around 2020 and decrease rapidly to global zero around the 2060s. Although the IPCC SR1.5 also assesses other pathways, these lead to higher warming levels. These include pathways that return warming to 1.5°C by 2100, but achieve this after an overshoot to as much as 1.9°C, which is clearly not holding warming "well below 2°C" as specified in Paris Agreement Article 2.1 and would be associated with climate risks, impacts and damages close to 2°C.

The principle part of this submission to the Talanoa Dialogue is on the question, "*How do we get there?*". To this end we examine the many PA-compatible pathways toward the 1.5°C limit and

[1] IPCC (2018) Special Report on Global Warming of 1.5°C, Chapter 2. http://www.ipcc.ch/report/sr15/

highlight those that appear most likely to maximize synergies with sustainability and feasibility criteria. Some key conclusions from our analysis are that:

- Rapid reductions in energy demand across all sectors are fundamental for 1.5°C compatible pathways that also limit negative emissions through carbon capture technologies.
- A rapid and almost complete phase-out of coal by 2050 in the power sector is a universal message, with the highest agreement across scientific publications. Crucially, most of this transformation needs to happen right now, because the use of coal in the power sector needs to be reduced from currently over 35% of global electricity supply to only 3-10% by 2030.
- At the same time, total coal use in energy and industry needs to be reduced to 60-80% below 2010 levels by 2030 and to up to 95% below 2010 levels by 2050.
- Natural gas, even if combined with Carbon Capture and Storage (CCS) is reduced sharply as well, to 8% (3–11%) of global electricity in 2050.
- With a high rate of electrification of transportation, substantial reductions in oil use are projected, with oil use by 2030 as much as 35% lower than in 2010, and 30-80% lower by 2050.
- Renewable energy technologies (excluding biomass) reach a particularly high share in electricity supply of 45-65% in 2030 and 70-85% in 2050.
- In addition, total primary energy needs to be supplied by renewable energy (excluding biomass) at a share of 50-65% by 2050[2], displacing fossil fuels from traditional markets for power generation, mobility and heating.
- 1.5°C compatible transformation will require significant additional investment worldwide in low-emission infrastructure as well as redirection of financial resources away from carbon-intensive investments. Global annual investments in low-carbon energy technologies overtake fossil investments already by around 2025 in 1.5°C pathways.

[2] Information on this was included by IPCC authors in the final draft of the SPM, but was not included in the final government-approved SPM

Where are we? – Climate impacts

The IPCC Special Report on Global Warming of 1.5°C provides a summary of the most recent research on the impacts of current levels of anthropogenic climate change and on expected impacts on land and ocean ecosystems and human societies of future warming. It builds upon, but substantially extends the assessment from the IPCC Fifth Assessment Report (AR5), given the rapid expansion of scientific literature since AR5. To cite just three examples from the IPCC SR1.5 Summary for Policymakers (SPM),

> "Climate models project robust differences in regional climate characteristics between present-day and global warming of 1.5°C, and between 1.5°C and 2°C. These differences include increases in: mean temperature in most land and ocean regions (*high confidence*), hot extremes in most inhabited regions (*high confidence*), heavy precipitation in several regions (*medium confidence*), and the probability of drought and precipitation deficits in some regions (*medium confidence*)."[3]

Furthermore, impacts due to sea-level rise are of particular importance for many coastal regions, including especially Small Island Developing States (SIDS):

> "By 2100, global mean sea level rise is projected to be around 0.1 metre lower with global warming of 1.5°C compared to 2°C (*medium confidence*). Sea level will continue to rise well beyond 2100 (*high confidence*), and the magnitude and rate of this rise depends on future emission pathways. A slower rate of sea level rise enables greater opportunities for adaptation in the human and ecological systems of small islands, low-lying coastal areas and deltas (*medium confidence*)."[4]

Earth system impacts of a changing climate can have direct consequences for human societies, especially those most vulnerable such as Least Developed Countries (LDCs):

> "Climate-related risks to health, livelihoods, food security, water supply, human security, and economic growth are projected to increase with global warming of 1.5°C and increase further with 2°C."[5]

> "Regions at disproportionately higher risk include Arctic ecosystems, dryland regions, small-island developing states, and least developed countries (*high confidence)*. … [L]imiting global warming to 1.5°C, compared with 2°C, could reduce the number of people both exposed to climate-related risks and susceptible to poverty by up to several hundred million by 2050 (*medium confidence*). "[6]

Given these risks and threats that increase from currently observed impacts at approximately 1.0°C of warming with respect to pre-industrial levels[7], and the increasing certainty that observable impacts can be attributed to each additional 0.5°C of warming ,[8] the key task is to

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[3] IPCC (2018) *Special Report on Global Warming of 1.5°C*, Summary for Policymakers ipcc.ch/sr15/pdf/sr15_spm_final.pdf §B1
[4] *Ibid*. SPM §B2
[5] *Ibid* SPM §B5
[6] *Ibid*. SPM §B5.1
[7] *Ibid*. SPM §A1
[8] Schleussner, C.F., P. Pfleiderer, and E.M. Fischer (2017) "In the observational record half a degree matters" *Nature Climate Change*, **7**(7), 460-462, doi:10.1038/nclimate3320. Schleussner, C.F. et al., (2016): "Differential climate impacts for policy relevant limits to global warming: the

determine the feasible pathways forward to avoid the worst impacts of climate change by limiting warming to 1.5°C or lower by the end of the century.

Where do we need to go? 1.5°C pathways in the literature

The long-term temperature goal (LTTG) of the Paris Agreement is defined in Article 2 as "Holding the increase in the global average temperature to well below 2°C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change". The emissions goals specified in Article 4 – peak global emissions "as soon as possible", followed by "rapid reductions thereafter" to reach zero net greenhouse gas emissions in the second half of this century – are to be determined "according to best available science" so as to be consistent with the LTTG.[9] The IPCC SR1.5 provides key input to operationalising Article 4.1 and defining the rate of emission reduction and timing of the achievement of net zero greenhouse gas emissions globally that are compatible with limited warming to 1.5°C.

One of the main tools assessed in the IPCC SR1.5 are Integrated Assessment Models (IAMs) that couple socioeconomic, energy-technical and climate systems to investigate how different assumptions about future developments will influence the space for climate change mitigation options.[10] Since the Paris Agreement, great effort has been made by IAM teams to extend to the challenging target of 1.5°C to their previous work on mitigation pathways taking into account recent trends in the energy system in particular.

There is substantial variation in both the level of peak warming (*i.e.* the degree of overshoot beyond 1.5°C) and the means used to achieve emissions reductions in the mitigation pathways assessed in IPCC SR1.5. Therefore, these pathways should not be seen *as* being a priori *equal in terms of their climate and sustainable development outcomes.*

Pathways compatible with the Paris Agreement: Limiting peak and end-century temperature rise

The Paris Agreement's long-term temperature goal is a strengthening of the previous goal of holding warming "below 2°C", as agreed in Cancun in 2010, and refers to "holding warming well below 2°C" and limiting it to 1.5°C.[11] Emissions pathways compatible with the Paris Agreement must increase significantly both the margin and likelihood by which warming is kept below 2°C when compared with "below 2°C" emissions pathways. Pathways compatible with the former "below 2°C" goal have a peak warming of 1.7-1.8°C, and have a 66% probability of holding warming during the 21st century below 2°C[12], but generally less than 50% probability of holding warming below 1.5°C. The strengthened temperature goal therefore requires a substantially higher probability of holding warming below 2°C and at least 66% of limiting end-century warming to 1.5°C.

case of 1.5°C and 2°C". *Earth System Dynamics*, **7**(2), 327-351, doi:10.5194/esd-7-327-2016; Schleussner *et al*. (2018) "1.5 °C Hotspots: Climate Hazards, Vulnerabilities, and Impacts" *Annu. Rev. Environ. Resour*.. 43:135–63. https:// doi.org/ 10.1146/annurev- environ-102017- 025835

[9] https://unfccc.int/process-and-meetings/the-paris-agreement/what-is-the-paris-agreement

[10] https://climateanalytics.org/publications/2018/integrated-assessment-models-what-are-they-and-how-do-they-arrive-at-their-conclusions/

[11] https://unfccc.int/process/conferences/the-big-picture/milestones/the-cancun-agreement s

[12] See e.g. UNEP emissions gap report 2015 released in the lead up to COP21: https://www.unenvironment.org/resources/emissions-gap-report-2015

However, many IAM pathways temporarily overshoot 1.5°C before the end of the century. As pointed out in the IPCC SR1.5, overshoot trajectories lead to higher impacts[13] and could result in irreversible changes to the Earth System. Furthermore, the required amount of Carbon Dioxide removal and geophysical uncertainties surrounding the effectiveness of such measures under pathways with high overshoot lead to questions as to their feasibility. Addressing this issue, the IPCC SR1.5 concluded that:

> "Reversing warming after an overshoot of 0.2°C or larger during this century would require upscaling and deployment of CDR at rates and volumes that might not be achievable given considerable implementation challenges (*medium confidence*). "[14]

The IPCC SR1.5 Summary for Policy makers assesses only 1.5°C-compatible classes of mitigation pathways with no- or limited-overshoot. These include: Pathways that limit median global warming to 1.5°C throughout the 21st century without exceeding that level ("no-overshoot") and those that drop well below 1.5°C by the end of the century (around 1.3°C warming by 2100) after a brief and limited overshoot of median peak warming below 1.6°C around the 2060s ("low-overshoot"). The low overshoot scenarios still have a 'as-likely-as-not' probability[15] of not exceeding 1.5°C throughout the century. For both these categories of pathways, total greenhouse gas emissions peak around 2020 and decrease rapidly to global zero around the 2060s. With the IPCC SR1.5 reflecting the best available science, it is clear that these pathways are compatible with the PA long-term temperature goal in its Article 2.1 and can be used for operationalising in Article 4.1.

Although the IPCC SR1.5 also assesses other pathways, these lead to higher warming levels. These include pathways that return warming to 1.5°C by 2100, but achieve this after an overshoot to as much as 1.9°C, which is clearly not "well below 2°C" as specified in PA Article 2.1 and would be associated with climate risks, impacts and damages close to 2°C. These pathways are therefore not compatible with the Paris Agreement. Indeed, IPCC SR1.5 SPM concludes:

> "Future climate-related risks depend on the rate, peak and duration of warming. In the aggregate they are larger if global warming exceeds 1.5°C before returning to that level by 2100 than if global warming gradually stabilizes at 1.5°C, especially if the peak temperature is high (e.g., about 2°C) (*high confidence*)."

How do we get there? Rapid transformations of energy supply and demand

A range of socioeconomic driving factors will influence the underlying trends that determine energy demand, and therefore indirectly GHG emissions. In the Integrated Assessment Model (IAM) community, baseline socioeconomic drivers are characterized through a set of Shared Socioeconomic Pathways (SSPs) that are classified in terms of a two-dimensional matrix along axes of "challenges to mitigation" and "challenges to adaptation."[16] Furthermore, IAMs make a number of assumptions about technology costs,

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[13] IPCC (2018) SPM §D1.1
[14] IPCC (2018) SPM §D1.2
[15] A 50-67% probability of temporarily overshooting 1.5°C
[16] O'Neill et al. (2017) "The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century" *Global Environmental Change*, **42**, 169-180, doi:10.1016/j.gloenvcha.2015.01.004

rates of expansion of capacity, future costs of fossil fuels, availability of different technologies and more.[17] Depending on the assumptions made as inputs to the models, and on the background information used to construct different scenarios, IAMs may also take into account additional targets such as sustainable development considerations. Many of the IAMs used in the IPCC SR1.5 evaluate options within a "cost-effectiveness" mode, meaning that a model deploys mitigation options in any region, any sector, at any time, so that overall (globally, and over the century), the warming limit is achieved at lowest cost. These models do not consider explicitly the avoided damages that will result from mitigation of climate change impacts, nor do they take into account co-benefits of mitigation strategies that arise from eliminating harmful emissions from fossil-fuel combustion, for example. Seen in this light, IAMs can be viewed as conservative when it comes to costs of climate change mitigation.

Overview of 1.5°C compatible scenarios

Given the background criteria discussed above, we examine ***1.5°C compatible*** scenarios from IAMs, focusing on the important tradeoffs between continuing fossil fuel consumption and the use of CCS, reliance on BECCS, or including relatively large amounts of "nature based solutions" (NBS).[18] Some key properties of most emissions pathways with low- or no-overshoot are:

- Emissions of all GHG (not just energy-system emissions of CO_2) in 2030 must be less than about 30 $GtCO_{2-eq}$/year, about half of the global aggregate emissions in 2030 implied by the current NDCs[19]
- Global zero CO_2 emissions by about 2050 and global zero total GHG emissions by the 2060s
- A rapid energy system transformation, with considerable foresight and planning on the part of nations worldwide
- Accelerated trends in decarbonization and energy efficiency across all sectors compared to 2°C pathways

More specifically, the IPCC SR1.5 SPM characterizes the diversity across 1.5°C pathways using "illustrative" low-overshoot pathways, and contrasts these with a high-overshoot pathway. These illustrative pathways each represent a highly diverse set of assumptions on population and economic growth projections and a range of socio-economic and sustainability considerations:

- o P1 is a 1.5°C compatible scenario and holds warming below 1.6°C (low-overshoot) driven by a low-energy-demand scenario focusing on the period to 2050 and innovations both in technologies and in social structures and behavior. Standards of living, especially in the global South, increase in line with Sustainable Development Goals, while the downsized global energy system allows decarbonization to proceed

[17] https://climateanalytics.org/publications/2018/integrated-assessment-models-what-are-they-and-how-do-they-arrive-at-their-conclusions/
[18] Bronson *et al*. (2017) "Natural Climate Solutions", *Proc. Nat. Acad. Sci*. **114** 11645-1160
[19] Rogelj et al. (2018) "Scenarios towards limiting global mean temperature increase below 1.5°C", *Nature Climate Change* **8**(02), 1750009 doi:10.1038/s41558-018-0091-3

rapidly. Potentially risky or uncertain strategies of fossil-fuel and bioenergy CCS are avoided, relying instead on afforestation for carbon dioxide removal.

- P2 is a 1.5°C compatible_low-overshoot 1.5°C pathway driven by a sustainability-focused scenario in which global cooperation and convergence of standards of living are emphasized. Low-carbon technological innovation, including efficiency measures and sustainable consumption patterns are characteristic of this scenario, as is a relatively low reliance on CCS technologies.
- P3 is a 1.5°C compatible_low-overshoot 1.5°C pathway representing a middle-of-the-road strategy that follows historical trends in energy use, efficiency and technological development patterns. Low-carbon energy system technologies are substituted for high-carbon technologies, with many behavioral and consumption patterns remaining similar.
- P4 is not a 1.5°C compatible pathway_and is essentially a below 2°C pathway, overshooting 1.5°C by 0.4°C for some decades, driven by a high-growth, high-consumption scenario in which initially high energy use, especially of fossil fuels, is compensated in the latter half of the century by CCS, especially through BECCS.

Even within this classification of scenarios there is a wide range of technology options used to achieve low- to no-overshoot pathways. Further criteria are needed to satisfy sustainability and feasibility criteria.

Use of large-scale carbon dioxide removal

All existing pathways for limiting warming to 1.5°C require some level of carbon dioxide removal (CDR)[20], but there is substantial variation in the amount and type of CDR employed.[21] Many pathways rely heavily on Bioenergy with Carbon Capture and Storage (BECCS), although some studies have also incorporated Direct Air Capture and Storage (DACS)[22]. There are a number of open questions about relying on either of these technologies at scale. In this analysis, we will privilege scenarios that do not rely on high negative emissions due to the uncertainty in technological development, potential for competition with other sustainability criteria; in the IPCC SR1.5 the maximum BECCS potential is assessed from the literature to be 5 $GtCO_2$/year.[23] Adherence to the precautionary principle requires that one should limit reliance on a technology for future developments until an absence of harm can be proved. CCS for fossil-fuel technologies, such as from coal and natural gas power generation, will be significantly more expensive than without CCS; rapidly decreasing costs for renewable energy and electricity storage mean that fossil CCS is less likely to be competitive with renewable sources of electricity combined with battery and other storage systems.

Some pathways eliminate the need for BECCS by relying more heavily on the land-use sector for CDR (through reforestation and afforestation).[24] As has been pointed out in the literature, many of these "nature based solutions" (NBS) choices must also be examined for limited potential in the long term (saturation, permanence of storage) and potential negative consequences for other parts of the earth

[20] IPCC (2018) SPM §C3
[21] Rogelj et al. (2018) *op cit*
[22] Strefler et al. (2018) "Between Scylla and Charybdis: Delayed mitigation narrows the passage between large-scale CDR and high costs" *Env. Res. Lett.* **13** 044015
[23] IPCC (2018) SPM §C3.2
[24] Bronson, *et al.* (2017) *op cit*

system when applied at large scale.[25] Once again, we draw the conclusion that sustainable Paris-compatible pathways will be ones that do not rely overly much on afforestation, assessed in IPCC SR1.5 as being a maximum of 3.6 $GtCO_2$/year.[26]

Primary energy demand

While all IAMs incorporate continued progress in energy intensity of economic development into their model structures, achieving the PA target will require an acceleration of these trends compared to the recent past. Enhanced energy efficiency measures also have the advantage that lower demand for the same energy services will reduce the requirements for renewable energy capacity to satisfy those needs.

The illustrative P1 scenario (Low Energy Demand, or LED) maps out potential technological transformations, while also explicitly taking other sustainable development considerations into account. Overall, the P1-LED pathway[27] shows how a focus on reducing demand-side emissions can enable a very low emissions scenario with minimal CDR requirements. Similar pathways arrive at the same conclusion, although the details of these pathways differ.[28] These points are summarized in Table 1.

Table 1 – Primary energy indicators for IPCC SR1.5 SPM illustrative pathways and median and range (inter-quartile) over all 1.5°C-compatible pathways[29]. Changes in energy demand (Total Primary Energy) and changes in non-biomass renewables and shares in total primary energy for non-biomass renewables and biomass in 2030 and 2050 compared to 2010 levels.

Scenario	Primary energy (2030 change from 2010)	Primary energy (2050 change from 2010)	Non-biomass renewable energy (2030 change from 2010)	Non-biomass renewable energy (2050 change from 2010)	Non-biomass renewable energy (% of total primary energy, 2050)	Biomass energy (% of total primary energy, 2050)
P1	-25%	-42%	433%	838%	57%	16%
P2	-11%	-6%	470%	1327%	43%	15%
P3	2%	10%	315%	878%	31%	22%
All 1.5°C pathways	-6% (0%, -12%)	9% (-12%, 27%)	323% (245%, 436%)	872% (576%, 1299%)	28% (22%, 43%)	27% (20%, 38%)

Fossil fuel phase-out

The variation in timing of fossil-fuel phase out in the representative 1.5°C compatible pathways (P1-3) represents well the variations found across the whole collection of no and low-overshoot 1.5°C pathways assessed in IPCC SR1.5 (Tables 2)

[25] Harper et al. (2018) "Land-use emissions play a critical role in land-based mitigation for Paris climate targets", *Nature Communications* 9:2938 DOI: 10.1038/ s41467-01 8-05340-z
[26] IPCC (2018) SPM §C3.2
[27] Grubler et al. (2018) "A low energy demand scenario for meeting the 1.5C target and sustainable development goals without negative emission technologies" *Nature Energy* **3** 515-527 https://doi.org/10.1038/s41560-018-0172-6
[28] van Vuuren et al. (2018) "Alternative pathways to the 1.5°C target reduce the need for negative emission technologies" *Nature Climate Change* **8**(5) 391-397 https://doi.org/10.1038/s41558-018-0119-8; Kriegler,et al.(2018) "Pathways limiting warmingto1.5°C: a tale of turning around in no time?" *Phil.Trans.R.Soc.A* **376**: 20160457
[29] IPCC SR1.5 scenario database https://data.ene.iiasa.ac.at/iamc-1.5c-explorer, accessed 22 October, 2018.

Table 2 – Fossil-fuel indicators IPCC SR1.5 SPM illustrative scenario and median and range (inter-quartile) over all 1.5°C-compatible pathways[30]. Reductions in fossil-fuel primary energy compared to 2010 for 2030, 2050 and 2100, and share of total primary energy supply for 2010, 2030 and 2050.

Fossil fuel	Pathway	2030 (change from 2010)	2050 (change from 2010)	2100 (change from 2010)	2010 (% primary energy)	2030 (% primary energy)	2050 (% primary energy)
Coal (no CCS)	P1	-78%	-97%	-100%	28%	8%	1%
	P2	-64%	-94%	-99%	27%	11%	2%
	P3	-82%	-100%	-100%	28%	5%	0%
	All 1.5°C pathways	-71% (-62%,-81%)	-94% (-92%,-98%)	-99% (-97%, -100%)	29%	9% (6%, 11%)	2% (0%, 3%)
Coal (total, incl. CCS)	P1	-78%	-97%	-100%	28%	8%	1%
	P2	-61%	-77%	-96%	27%	12%	7%
	P3	-75%	-73%	-100%	28%	7%	7%
	All 1.5°C pathways	-69% (-59%, -78%	-83% (-74%, -95%)	-92% (-75%, -99%)	29%	10% (7%, 12%)	5% (1%, 7%)
Oil (no CCS)	P1	-36%	-87%	-100%	34%	29%	8%
	P2	-14%	-66%	-92%	36%	35%	13%
	P3	-3%	-81%	-98%	35%	33%	6%
	All 1.5°C pathways	-11% (-35%, +3%)	-64% (-40%, -78%)	-86% (-74%, -94%)	35%	33% (26%, 38%)	12% (7%,20%)
Oil (total, incl. CCS)	P1	-36%	-87%	-100%	34%	29%	8%
	P2	-13%	-50%	-88%	36%	35%	19%
	P3	-3%	-81%	-98%	35%	33%	6%
	All 1.5°C pathways	-9% (-34%, +3%)	-60% (-30%, -78%)	-85% (-71%, -97%)	34%	31% (26%, 36%)	13% (8%, 19%)
Natural gas (no CCS)	P1	-25%	-73%	-98%	21%	21%	10%
	P2	-22%	-84%	-96%	22%	19%	4%
	P3	+21%	-29%	-50%	21%	25%	14%
	All 1.5°C pathways	-7% (-30%,+9%)	-55% (-36%, -73%)	-75% (-92%,-60%)	22%	21% (17%, 26%)	9% (5%, 14%)
NG (total, incl. CCS)	P1	-25%	-73%	-98%	21%	21%	10%
	P2	-20%	-53%	-79%	22%	20%	11%
	P3	+33%	+21%	-50%	21%	27%	23%
	All 1.5°C pathways	+2% (-26%,+21%)	-27% (-56%,+6%)	-61% (-27% ,-81%)	22%	23% (19%, 27%)	13% (9%, 22%)

Coal

One point on which most 1.5°C compatible emissions pathways from IAMs agree is that coal, as the most greenhouse-gas intensive fossil fuel, must be rapidly phased-out. The IPCC SR1.5 SPM notes that "… the use of coal shows a steep reduction in all pathways and would be reduced to close to 0% (0–2%) of electricity (*high confidence*)" by 2050. By analysing the publicly available IPCC SR1.5 pathway data, we find most of this transformation needs to happen right now: the use of coal in the power sector needs to be reduced from currently over 35%[31] of global electricity supply to only 3-10%[32] by 2030.

Compared to other pathways, this early reduction is especially clear for P1, again faster in the 2020-2030 period, but holds generally for any scenario that does not rely heavily on CCS over time. Table 2 shows results for world coal consumption, both unabated (*i.e.* without CCS) and with CCS, using the marker

[30] IPCC SR1.5 scenario database https://data.ene.iiasa.ac.at/iamc-1.5c-explorer, accessed 22 October, 2018.
[31] https://www.iea.org/tcep/power/coal/, accessed 26 October, 2018.
[32] IPCC SR1.5 scenario database https://data.ene.iiasa.ac.at/iamc-1.5c-explorer, accessed 22 October, 2018.

scenarios of the IPCC SR1.5 as guidelines. Many IAMs have scenarios that rely on coal for electricity generation together with CCS, there is a long tail of total coal consumption into the second half of the century in some cases. The P1 scenario clearly tends toward the lower end of the range of consumption in IAMs, consistent with the scenario's focus on energy efficiency and explicit avoidance of CCS. The immediate reduction of coal in the 2010-2020 period in the P1 scenario can be seen as unrealistic, as it seems inconsistent with actual developments over 2010 to 2018, so that to remain consistent with P1, actual coal use would have to phase out even faster in the 2020-2030 period.

However, given the very slow advance of fossil-fuel CCS over the past two decades, a time period over which the technology was to have been developed, strong doubt can be cast on whether this will become a viable part of a low-carbon future. Aside from the lack of significant technological progress to-date, two key points work against fossil-fuel CCS in a near-zero-carbon energy system. First, the cost of CCS added to current power plants or as part of any new electricity generation will necessarily add to the cost of generation. Already, renewables, increasingly even with battery storage, are competitive with coal-power generation in many parts of the world and that cost advantage will only grow over time. Second, even with CCS, coal and natural gas power is not emission free. The International Energy Agency assumes that the CO_2 intensity of coal power with CCS will still be about 100g/kWh[33]; in a system that should reach zero-net-carbon emissions by mid-century, this would represent a high-emissions technology.

Oil

From Table 2 we see that as opposed to coal and natural gas, for oil consumption, there is virtually no use of CCS in any models, since oil use for electricity generation becomes vanishingly small. The P1 pathway separates itself from other IAM scenarios is in the estimates for speed in reduction for consumption of oil. Whereas the other illustrative scenarios show a decrease in oil consumption by 2030 of approximately 3%-13% (with much stronger decrease by 2050), the P1 pathway shows a decrease of 36% by 2030 and nearly 90% by 2050. One of the features of the energy efficiency pathway in the LED scenario that forms the basis for the P1 pathway is the recognition of the advantages of electrification in the transportation sector in terms of final energy consumption reduction for the same level of energy services. For example, electric vehicles, assuming electricity sources are renewable and not from thermal generation, require a factor of three to five times less primary energy per kilometer traveled. Other factors in the P1 pathway are continued rapid urbanization and increased use of public and shared-mobility modes, leading to overall higher efficiency of the transport sector.

Natural Gas

Consumption of natural gas shows the greatest variation between pathways. Again, the picture is most clear – and with highest agreement – in the electricity sector, with the IPCC SR1.5 SPM noting that "… the use of CCS would allow the electricity generation share of gas to be approximately 8% (3–11% interquartile range) of global electricity in 2050", but total (all sectors) use of natural gas in the primary energy mix varies between a 56% decline from 2010 levels to a 6% increase by that time. Whereas many IAMs use natural gas as a bridge to a low-carbon future, that is not universally the case as demonstrated by the results shown in Table 2. Once again we see that the P1 pathway lies towards the lower end of the

[33] IEA (2017) *Energy Technology Perspectives 2017: Catalyzing Energy Technology Transformations*. International Energy Agency (IEA). Paris, France

distribution, although not as clearly separated from the P2 pathway. What is clear from the results shown in Table 2 is that the P1 pathway is at the lower end of the consumption projections for all three fossil fuels simultaneously.

To reiterate, the P1 pathway explicitly excludes the use of fossil-fuel CCS. For much the same reason as discussed above in the case of coal-fired power, a large-scale build-out of natural gas capacity with the increased costs and decreased net output power of adding CCS is difficult to imagine at this point in time. Furthermore, even in less ambitious mitigation scenarios, such as those of the IEA[34], there are implications for use of natural gas power-generating capacity. As modeled in the ETP, both with and without CCS capability capacity factors already start to decrease beginning in about 2040. Therefore, capacity built even in the near future will likely not be utilized for the full technical lifetime, making investments highly risky.

Rapidly ramping up renewable energy

The rapid increase in installations of renewable energy over the past decade, and particularly of solar pv and wind capacity, has caught nearly all observers by surprise, including energy system modellers.[35] As capacity installation has increased a virtuous cycle has developed in which renewables have quickly become economically competitive with traditional fossil fuel electricity sources in many cases, due to economies of scales and learning effects. Greatly accelerated climate mitigation action in line with the targets of the Paris Agreement should now be possible at significantly lower costs than anticipated even a few years ago.[36]

The IPCC SR1.5 SPM shows that in Paris Compatible pathways renewable are projected to supply 45–65% of electricity by 2030 and 70–85% of electricity by 2050. Currently, non-hydroelectric power generation is growing at 15%/year and has grown to over 8% of total electricity supply.[37] Adding to this the more slowly-growing production from hydropower and the total renewable electricity supply worldwide is approximately 25%. This rate of growth will have to continue and even accelerate for the next few decades but is one of the promising signs of energy system transformation.

Leveling the playing field

One of the continuing narratives in the energy system is the insistence that renewable energy technologies are not ready for widespread adoption because of perceived cost disadvantages. When comparing the operating costs of some existing fossil-fuel power plants with the investment needs for renewables and for newer technologies such as electric vehicles, there may be some truth to these claims. However, this line of argument leaves out the negative externalities created by the consumption of fossil fuels, even beyond the impacts of climate change. Internalizing, or taking fully into account, the health impacts of coal and petroleum combustion, for example, would often tip the scale in favour of renewables.

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[34] IEA (2017) *ibid*
[35] Creutzig et al. (2017) "The underestimated potential of solar energy to mitigate climate change" *Nature Energy* **2** 17140
[36] http://climateanalytics.org/briefings/keeping-up-with-the-renewable-revolution-updating-the-ndcs.html
[37] BP (2018) Statistical Review of World Energy 2018

Investments pattern changes and avoiding stranded assets

The decrease in use of fossil-fuels and increase in renewables is associated with a major shift in investments, where global annual investments in low-carbon energy technologies[38] overtake fossil investments already by around 2025 in 1.5°C pathways[39]. The SPM shows that annual investment in low-carbon energy technologies and energy efficiency increase rapidly by a factor of 4-5 by 2050 compared to 2015. Compared to 2°C pathways, total energy-related investments in both supply and demand side increase by 12%. The underlying report shows that annual investments in renewables for power generation (excl. biomass) increase in 1.5°C pathways by 200 billion USD compared to current levels, while investments in fossil-fuel extraction and conversion[40] decline by that same amount and investments in fossil-fuel powered electricity without CCS reduce by around 100 billion USD. Investments are further higher in energy efficiency, the total of nuclear and fossil-fuel with CCS, and in electricity transmission, distribution and storage. (IPCC SR1.5 Figure 2.27).

The corollary to the positive investment changes in renewable energy and energy efficiency needed to achieve the Paris Agreement targets is that there is already a large amount of carbon-intensive infrastructure already in place, and that to a large extent, further investment in new, long-lived fossil-fuel infrastructure should be avoided.[41]

Conclusion

The long-term temperature goal in Article 2 of the Paris Agreement is operationalized in its Article 4 describing a global emissions reductions pathway "in accordance with best available science", specifying peaking of emissions as soon as possible and rapidly decreasing thereafter and achieving net-zero GHG emissions in the second-half of the century. The details of how these emissions reductions are to be realized are now informed by the IPCC Special Report on 1.5°C; in this Submission we have analyzed characteristics of some of the options available for mitigation. The IPCC SR1.5 shows that limiting global warming to achieve the Paris Agreement targets is technically and economically feasible under a variety of plausible scenarios for socioeconomic and technical development. The necessary reductions in both CO_2 and total GHG emissions are summarized in Table 3.

Table 3 - Summary of emissions reductions needed, as presented in the IPCC SR1.5 Summary for Policymakers and from IPCC SR1.5, Chap. 2, Table 2.4.

Target variable	Emissions decrease (IPCC SR1.5 SPM)
CO2 emissions change by 2030	Decrease by 40% - 59% (interquartile range)
CO2 emissions change by 2050	Decrease by 91% - 104% (interquartile range)
CO2 emissions – year of global zero	2037-2054 (no-OS); 2047-2055 (low-OS)
Kyoto-GHG emissions change by 2030	Decrease by 38% - 55% (interquartile range)
Kyoto-GHG emissions change by 2050	Decrease by 81% - 93% (interquartile range)
Kyoto-GHG emissions – year of global zero	2044-post-2100 (no-OS); 2061-2080 (low-OS)

[38] Includes nuclear and fossil-fuel CCS - no data on renewables available separately at this moment.
[39] IPCC (2018) *op cit.* Chapter 2
[40] Further information on this was included by IPCC authors, but was removed from the final government-approved SPM. The information referred to a decline in fossil-fuel extraction and conversion of 60% below 2015 levels by 2050 in 1.5°C pathways
[41] Davis, et al. (2010) "Future CO_2 Emissions and Climate Change from Existing Energy Infrastructure" *Science* **329**, 1330-1333; Bertram et al. (2015) "Carbon lock-in through capital stock inertia associated with weak near-term climate policies" *Technological Forecasting & Social Change* **90** 62– 72; Edenhofer et al. (2018) "Reports of coal's terminal decline may be exaggerated" *Environ. Re s. Lett.* **13** (2018) 024019

Technologies exist to make the necessary energy system transformation to limit warming in accordance with the Paris Agreement. As discussed in this submission, a combination of increasing energy efficiency, rapid phase-out of fossil fuel combustion and continued progress in the rate of expansion of renewable energy deployment will all be needed. Limiting reliance on CCS for fossil fuels, while recognizing the need for some measure of carbon capture technology to compensate emissions in sectors for which complete decarbonization will be difficult, as well as reversing the current trend of deforestation, are also important parts of meeting the Paris Agreement.