ANALYSIS AND TRANSLATION OF GLOBAL SCENARIOS TO INFORM PARIS-ALIGNED PATHWAYS FOR THE ENERGY SYSTEM

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Executive Summary

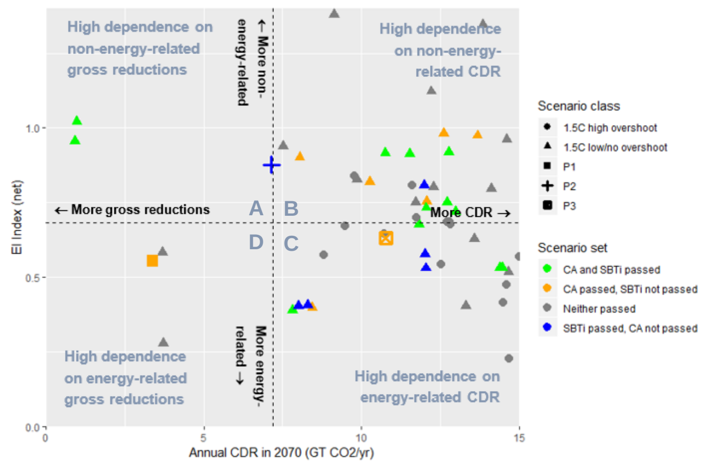
Scenarios that limit end-of-century warming to 1.5°C demonstrate clear trade-offs between pursuing steep, near-term emissions reductions across all sectors of the energy system and increased reliance on the future deployment of carbon dioxide removal. In all 1.5C low/no-overshoot scenarios in the SR15 database, net energy-related CO2 emissions decrease by 62% (interquartile range: 51%-70%) between 2020 and 2035. The allocation of energy-related CO2 budgets among primary energy products including oil, gas, and biomass with and without CO2 capture and storage varies across scenarios, primarily as a result of experimental conditions that explicitly or implicitly limit scenario reliance on bioenergy with CO2 capture and storage or total carbon dioxide removal (CDR) and differences in land-use related emissions. Smaller differences in the allocation of energy-related CO2 budgets result from the balance of reducing the emissions intensity of energy and reducing the energy intensity of economic growth, which varies across models and in some cases, across scenarios that align with narrative-driven shared socioeconomic pathways.

Three approaches to identifying "Paris-aligned scenarios" that limit warming to 1.5°C are examined, but none of them fulfill the SBTi's requirement for new sector pathways to clearly demonstrate that the emissions budget is reasonably shared with sectors not covered. Closer inspection reveals that some scenarios classified as 1.5°C no overshoot rely on land-use CO2 emissions that become abruptly negative as soon as 2022, approximately doubling the allowable energy and industrial process-related CO2 emissions by comparison to commonly used budgets.

The extent of scenario reliance on CDR – both within the energy system through bioenergy with CO2 capture and storage and outside the energy system, mainly through afforestation and reforestation – is directly addressed by two of the three examined approaches and indirectly addressed by one approach, but some scenarios that rely on the sustained removal of more than 14 GT CO2/year later in the century are still included by two of those approaches. Projections of industrial and land-use related CDR at such scales – equivalent to more than 40% of all energy and industrial CO2 emissions in 2018 – are faced with serious concerns over technical and political feasibility, as well as potential conflicts with Sustainable Development Goals.

This paper recommends that benchmarking authorities including the SBTi examine (1) the relative contribution of the energy system to global mitigation and (2) the scenario's reliance on CDR as a joint framework for identifying Paris-aligned energy system transformations. The two metrics, defined as (1) energy-related emissions divided by the absolute value of global emissions in forthcoming decades and (2) cumulative CDR over the century, may be drawn into a quadrant chart that classifies scenarios achieving similar levels of warming into those with (A) heavy reliance on non-energy related gross reductions, (B) heavy reliance on non-energy related CDR, (C) heavy reliance on energy-related CDR, and (D) heavy reliance on energy-related gross reductions.

Different strategies are proposed for how a science-based target setting method should incorporate CDR depending on the preferences of the initiative and the quadrant classification of the scenario. Scenarios in quadrant (D) are considered the most robust and aligned with the SBTi's Sector Development Framework, while scenarios in quadrant (A) should never be included in the calculation of energy system pathways. Some considerations may warrant the inclusion of scenarios in quadrants (B) and (C), but steps would need to be taken to ensure that the role of CDR in the scenario is adequately reflected by the method. This is particularly important to consider alongside the development of the SBTi's Net-Zero principles due to the potential for double-counting of emissions removals where companies achieve their targets in part through the deployment of CDR. Steps may include utilizing a primary energy sector-wide pathway, as opposed to product-specific pathways, for scenarios in quadrant (C) or explicitly allocating removals to sectors (or subsectors) and target-setting companies for scenarios in quadrant (B). The interpretation of scenarios in quadrant (D) is more straightforward due to those scenarios' allocation of gross reductions, rather than removals, to the energy system and limited reliance on CDR.



EI Index in 2040 vs Annual CDR in 2070. Chart is divided into quadrants where the vertical line demarcates scenarios with over/under 7.2 GT CO2/year and the horizontal line demarcates scenarios with EI Indices over/under the 1.5C low/no-overshoot median. Scenarios with >15 GT CDR/yr are not shown. (Reproduced from Figure 11 in Section 5.)

Lastly, it is suggested that scenarios in quadrant (D) are the most appropriate for determining SBT *net* emissions pathways for subsectors of the energy system, while a range of scenarios in quadrants (B) and (C) may be used to determine the minimum *gross* emissions pathways for those subsectors. The difference between subsector pathway emissions for scenarios in quadrant (D) and scenarios in quadrants (B) and (C) could indicate the proportion of subsector targets that may be achieved through the use of removals, as opposed to gross reductions.

In this assessment, three scenarios, including the archetype scenario P1, which depicts a 70% reduction in energy-related CO2 emissions (80% reduction in coal, 60% reduction in gas, and 50% reduction in gas) between 2020 and 2035, are classified in quadrant (D). Most other 1.5C low/no-overshoot scenarios are classified in quadrants (B) and (C). However, adjustments to the CDR cut-off metric could result in the migration of approximately four scenarios from quadrant (C) to (D).

Glossary

- **ACT:** Methodology piloted by CDP and Ademe that assesses company readiness to transition to a low-carbon world based on a future-oriented, sector specific approach;
- **Afforestation/reforestation (AR):** Planting of forests on lands that have not historically contained forests or that have previously contained forests. AR is commonly depicted as the largest contributor to land-use related carbon sequestration;
- **Archetype scenarios:** demonstrative climate mitigation scenarios that correspond to broad socioeconomic narratives that are used as a prevalent analytical framework in SR15. Three of the scenarios are drawn from the SSP-RCP1.9 experiment and one is drawn from a new, "Low Energy Demands" scenario experiment;
- **Bioenergy:** Energy produced by biomass. In many cases, bioenergy is considered "carbon neutral" because combustion-related CO2 emissions are ideally balanced by CO2 that is sequestered by biomass feedstock;
- **Carbon Analytics 1.5C set (CA 1.5C set):** A set of 21 scenarios drawn from the SR15 Scenario Database through a filter process, as described in *Global and regional coal phase-out requirements* (Yanguas Parra, et al. 2019), used to determine Paris-aligned coal phase-out rates;
- **Carbon dioxide capture and storage (CCS):** A process used to capture CO2,
- **Carbon dioxide removal (CDR):** "Anthropogenic activities removing CO2 from the atmosphere and durably storing it in geological, terrestrial, or ocean reservoirs, or in products. It includes existing and potential anthropogenic enhancement of biological or geochemical sinks and direct air capture and storage, but excludes natural CO2 uptake not directly caused by human activities (Masson-Delmotte, et al. 2018);"
- **Integrated assessment model (IAM):** Quantitative models used to study the impact of various policy decisions and socioeconomic changes on global climate, primarily by modeling the greenhouse gas emissions and CO2 removals associated with economic and natural processes (Weyant 2017);
- **The Intergovernmental Panel on Climate Change (IPCC):** United Nations body for assessing the science related to climate change;
- **IPCC's Special Report on Global Warming of 1.5C (SR15**): A Special Report requested by the United Nations 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. The report includes over 6,000 scientific references and was prepared by 91 authors from 40 countries;
- **Key indicator (KI):** Metrics defined in section 5 that are used to highlight differences between scenarios that influence the pace and structure of the energy transition depicted by each scenario, and to gesture toward potential metrics that can be used in PE sector SBT and ACT methodologies;

- **Long-term temperature goal (LTTG):** a specific level of global average warming in 2100 compared to pre-industrial levels;
- **Science Based Target (SBT):** Targets that are in line with what the latest climate science says is necessary to meet the goals of the Paris Agreement – to limit global warming to well-below 2°C above pre-industrial levels and pursue efforts to limit warming to 1.5°C;
- **Science Based Targets initiative 1.5C set (SBTi 1.5C set):** A set of 20 scenarios drawn from the SR15 Scenario Database through a filter process, as described in *Foundations of Science-Based Target Setting* (2019), to determine 1.5C Paris-aligned absolute contraction emissions reduction rates;
- **Science Based Target methodology:** Instructive frameworks that may be used by companies to set emissions reduction targets consistent with the best available climate science (Science Based Targets initiative 2019);
- **Sector Development Framework (SDF):** guidelines and criteria for how the SBTi expands its sector-specific target-setting methods and resources;
- **Sustainable Development Goals (SDGs):** "The 17 global goals for development for all countries established by the United Nations through a participatory process and elaborated in the 2030 Agenda for Sustainable Development, including ending poverty and hunger; ensuring health and well-being, education, gender equality, clean water and energy, and decent work; building and ensuring resilient and sustainable infrastructure, cities and consumption; reducing inequalities; protecting land and water ecosystems; promoting peace, justice and partnerships; and taking urgent action on climate change (Masson-Delmotte, et al. 2018);"
- **SR15 Scenario Database:** a collection of 411 different IAM scenarios that were subject to in-depth analysis and discussion in the IPCC's Special Report on Global Warming of 1.5C;
- **SR15 1.5C low/no overshoot set:** All scenarios in the SR15 scenario database that, if fully achieved, would limit peak warming to below 1.5C over the entire century with a 50-66% probability (i.e., no overshoot) or that limit warming in 2100 to 1.5C with at least a 50% probability, but temporarily exceed 1.5C earlier with a 50-67% probability (i.e., low overshoot), as assessed by the MAGICC6 simplified climate model;
- **Temperature overshoot:** global warming above a specified long-term temperature goal, which is then reversed by the sustained removal of CO_2 from the atmosphere in order to achieve the long-term temperature goal.

1. Introduction

The overarching science is clear: our global energy system needs to decarbonize as fast as possible through a combination of reduced energy consumption, electrification, and decarbonization of electricity and fuel (Rogelj, et al. 2018, 129). Yet, the specifics are deceptively complex and will critically affect both the likelihood of limiting warming and the achievement of Sustainable Development Goals (SDGs). An assessment of integrated assessment model (IAM) scenarios enables us to understand the range of possible energy system transitions; untangle their implications and assumptions, particularly as they relate to carbon dioxide removal (CDR) across systems, bioenergy, and timing of mitigation; and determine useful framings for primary energy (PE) and power sector Science Based Target (SBT) methods.

The main goals of this paper are to provide clear insight into 1.5C- (and to a lesser extent, well-below 2C-) aligned energy system transitions and to examine key indicators (KI) of progress. In this report, KIs have two, distinct functions: to highlight differences between scenarios that influence the pace and structure of the energy transition depicted by each scenario, and to gesture toward potential metrics that can be used in PE and power sector SBT and ACT methods. A secondary goal of this paper is to assess the consistency of specific scenarios and groupings of scenarios with the requirements of the SBTi Sector Development Framework (SDF) and the mission of the SBTi.

Outline

In Section 2, five different approaches to identifying Paris-aligned scenarios are compared. Next in Section 3, principles of the SBTi SDF are reviewed. In Section 4, five characteristics of the energy system transition are examined in overview, and following in Section 5, KIs for the PE sector and PE products are defined and examined to shed light on the range of sector transitions that may limit warming to 1.5C. In Section 6, KIs for the power sector are defined and examined. Section 7 contextualizes the preceding assessments with an emphasis on the existing scientific literature, and Section 8 offers suggestions on scenario usages that are consistent with the mission of the SBTi. Section 9 is a conclusion that reviews the goals and outcomes of the report.

2. Assessing climate scenarios

SBT methodologies, which are instructive frameworks used by companies to set emissions reduction targets, use climate scenarios to align with the best available science. Scenarios are modeled under a wide range of experimental conditions in order to evaluate alternative futures, both desirable and undesirable. Scenarios that achieve the same long-term temperature goal (LTTG) may vary enormously in terms of energy and land use requirements, technology deployment, and temperature overshoot; with critical implications for risk of failing to limit warming, sustainability (including, but not limited to food and water security), regional impacts, and economic development. Most scenarios examined in this paper have been drawn from the IAMC 1.5°C Scenario Explorer and Data hosted by IIASA (SR15 Scenario Database), which is a collection of 411 different scenarios that were also subject to in-depth analysis and discussion in the IPCC's Special Report on Global Warming of 1.5C (SR15) (Huppman, et al. 2019) (V. Masson-Delmotte 2018).

Various attempts have been made to identify Paris-aligned scenarios (Yanguas Parra, et al. 2019) (Science Based Targets initiative 2019) (Rogelj, Huppmann, et al. 2019) (Grant and Coffin 2019). They tend to focus on codifying Articles 2.1 and 4.1 of the Paris Agreement, which define the objectives of "holding" warming to well below 2C and "pursuing efforts to limit" warming to 1.5C and specify reaching a "global peaking of greenhouse gas emissions as soon as possible […] and to undertake rapid reductions thereafter in accordance with best available science […] so as to achieve [net-zero GHG emissions] in the second half of the century." In Table 1, five approaches to determining Paris-aligned scenarios that have been released since the publication of SR15 are compared.

Table 1: Five approaches to determining "Paris-aligned" scenarios

Name	Warming in 2100 (LTTG)	Overshoot	Risk profile and emissions peak	Sustainability and SDGs	CCS constraint	Number of scenarios	Usage
SBTi 1.5C (Science Based Targets initiative 2019)	Below 1.5C, 50-67% probability	Low/no overshoot	(1) GHG budget must not be exceeded before net-zero, minimizing reliance on late-century CDR; (2) GHG emissions peak around 2020; (3) least ambitious 20th percentile are removed	None	None	20	Determine global GHG emissions reduction rates
SBTi well-below 2C	Below 2C, >67% probability	No overshoot	Same as SBTi 1.5C	None	None	28 + ETP B2DS (2017)	Same as SBTi 1.5C

Climate Analytics (Yanguas Parra, et al. 2019)	Below 1.5C, 50-67% probability	Low/no overshoot	Limit BECCS to 0-5 GT CO2/yr and afforestation/reforestation (AR) to 0-3.6 GT CO2/yr in 2050[1]		None	19[2]	Assess regional coal phase-out rates
Carbon Tracker Initiative (Grant and Coffin 2019)	Below 1.5C, 50-67% probability; or IEA B2DS, SDS (see below)	Low/no overshoot or see below	Limited to P1 and P2 archetypes, which entail rapid, near-term emissions peak and decline with no or low reliance on CCS, limited total CDR, and strong synergies with SDGs; or see below			4	Assess coal, oil, and gas Paris-aligned transitions
IEA SDS (International Energy Agency 2018)	Below 1.8C, 66% probability (approx.)	No overshoot	CO2 emissions peak around 2020	Limit air pollution and pursue universal energy access	Bottom-up estimates CCS potential	1	Determine Paris-aligned regional energy pathways
A new scenario logic for the Paris Agreement (Rogelj, Huppmann, et al. 2019)	User explicitly sets (1) level of peak warming, (2) timing of peak warming, and (3) temperature decline after net-zero. These collectively determine warming in 2100 and overshoot with respect to a given risk profile and emissions peak			None	Optional	N/A	Open-ended

This report draws from each interpretation of Paris-alignment to assess energy system transitions. In most analyses, the SBTi 1.5C set and the CA 1.5C set are compared to the unfiltered collection of 1.5C low/no overshoot pathways included in SR15 ("1.5C low/no overshoot set") and three well-understood archetype scenarios (P1, P2, and P3)[3]. Archetype scenarios are used as a prevalent analytical framework in SR15 and reflect broad narratives about how the future might evolve (Figure 1). The underlying narratives that guide the model configuration corresponding to each archetype scenario are shown in Table 2. The 1.5C low/no overshoot set includes all scenarios in the SR15 scenario database that, if fully achieved, would limit peak warming to below 1.5C over the entire century with a 50-66% probability (i.e., no overshoot) or that limit warming in 2100 to 1.5C with at least a 50% probability, but temporarily exceed 1.5C earlier with a 50-67% probability (i.e., low overshoot)[4]. Although SR15 compares the synergies and trade-offs of different scenarios with various climate risks, technical barriers, and SDGs, the authors do not assess the Paris-alignment of individual scenarios or scenario groupings (IPCC 2018, 12-17) (Hoegh-Guldberg, et al. 2018, 265-271) (J. Roy 2018); rather, they specify that the collection of examined scenarios is an "ensemble of opportunity" that should be understood alongside an assessment of the underlying experiments (Rogelj, et al. 2018, 109). Accordingly, it should be

[1] SR15 concludes that the CO2 sequestration potential of BECCS and afforestation/reforestation are limited to these ranges in 2050, as a result of biogeochemical and economic constraints (IPCC 2018, 17).
[2] See Supplementary Text 2 for full description of CA's filter approach
[3] P4, which belongs to a separate class of high-overshoot scenarios is not examined here
[4] Classifications are based on global GHG emissions pathways assessed with the MAGICC simplified climate model

assumed that the 1.5C low/no overshoot set *does not* represent a collection of Paris-aligned scenarios, and it is included in this paper mainly for reference. In Supplementary Text 1, the SBTi well-below 2C (WB-2C) set is compared to the IEA ETP 2017 B2DS and IEA WEO 2019 SDS.

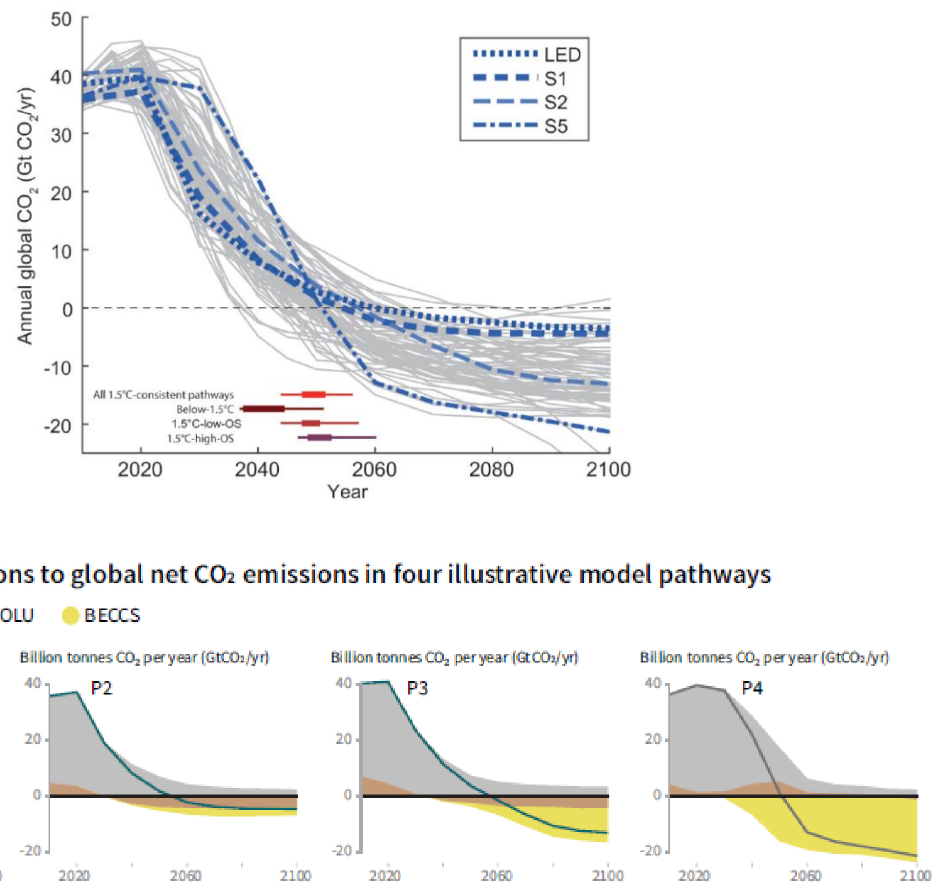


Figure 1: Global net CO_2 emissions in the low/no-overshoot 1.5°C set (grey) with archetype scenarios in blue (top) and breakdown of contributions to global net CO2 emissions in four archetype scenarios (bottom).

Table 2: Description of archetype scenarios included in SR15

Archetype	Description	Society's mitigation capability	Society's adaptation capability[5]	Paris alignment
P1 (Low Energy Development)	Rapid improvements in the energy efficiency of end-use sectors. No reliance on CCS (Grubler, et al. 2018).	Unspecified	Unspecified	Included in the CA and Carbon Tracker Initiative (CTI) sets; but excluded from the SBTi 1.5C set

[5] In Table 2, mitigation capability and adaptation capability are the inverse of "challenges to mitigation" and "challenges to adaptation" in Riahi et al. (2016). E.g., "high adaptation capability" translates to "low challenges to adaptation."

				due to overshooting the GHG budget before net-zero
P2 (Sustainability)	Gradual, but pervasive, progress toward the achievement of SDGs. Heightened environmental awareness leads to reduced material consumption, low support for fossil development, and the tendency toward a mixed, zero-carbon energy portfolio (including limited amounts of biomass, fossil with CCS, and nuclear) (Riahi, et al. 2016).	High	High	Included in the CTI and SBTi 1.5C sets, but excluded from the CA set due to high AR-related carbon sequestration in 2050
P3 (Middle of the Road)	Socioeconomic trends do not deviate markedly from historical patterns. Continued moderate support for fossil development, alongside the development of biomass and CCS technologies. (Riahi, et al. 2016)	Medium	Medium	Included in the CA 1.5C set, but excluded from the CTI set due to high reliance on CDR and from the SBTi 1.5C set for overshooting the GHG budget before reaching net zero emissions
P4 (Fossil-Fueled Development)	Rapid economic and technological development with a strong preference for the continued support of fossil fuels, resulting in a high degree of reliance on CCS and the need for increasingly productive land (Riahi, et al. 2016).	Low	High	Excluded from all Paris-aligned scenario sets due to high overshoot

3. Principles of the Sector Development Framework

The Sector Development Framework (SDF) is a set of guidelines meant to ensure that new sector pathways are fully aligned with the principles of the SBTi and that pathways and allocation mechanisms have been robustly determined (Science Based Targets initiative 2017). It includes emissions budget allocation criteria (Table 2), which are particularly important to consider in the selection of energy system subsector pathways, as well as specifying procedural and consultative requirements. In order to examine scenarios with respect to the budget allocation criteria, this paper will assess scenarios' energy-related emissions pathways relative to non-energy related emissions, as well as assessing scenarios' power-related emissions pathways relative to non-power related emissions.

Table 3: SDF emissions budget allocation criteria and their relevance to energy sector pathway assessment

Emissions budget allocation criteria[6]	Relevance to pathway assessment
(1) In the development of **new SECTORS**, the developer must demonstrate through a conservative method that the allocation of the emissions budget is reasonably shared among other not covered sectors	Global emissions budget should be reasonably shared between **energy-related emissions pathway** and non-energy-related emissions pathways (i.e., AFOLU emissions, industrial process-related emissions, other direct emissions)
(2) Ideally, the allocation of an emissions budget for a **specific subsector** (e.g., maritime freight) should be done in parallel with the allocation of emissions budgets for complementary subsectors (e.g., all other subsectors covered under 'other transport'). If the developer is planning to develop a pathway for only one subsector, the emissions pathway for this subsector should be at least as ambitious as that of the sector from which the subsector pathway is derived (e.g., the pathway for maritime freight should be at least as ambitious as the pathway for 'other transport').	The allocation of all **PE product emissions pathways** should be conducted in parallel; or if only one PE product emissions pathway is developed, it should be at least as ambitious as that of the PE sector overall.

Additionally, the SDF specifies that all scenario assumptions should be stated and justified, and that the developer may conduct a high-level impact assessment of socioeconomic implications, environmental impacts, carbon leakage, impacts on biodiversity and natural ecosystems, and competition with SDGs, in part due to the inclusion of contentious technologies or measures embedded in the pathway. These guidelines overlap with some of the Paris-aligned scenario principles examined in Section 2 and are critically examined throughout.

4. Characteristics of the energy system transition

In this section, five characteristics of the energy system transition are examined. The first four, as defined in Chapter 2 of SR15, are "limits on the increase of final energy demand, reductions in the carbon intensity of electricity, increases in the share of final energy provided by electricity, and reductions in the carbon intensity of final energy other than electricity" (Rogelj, et al. 2018,

[6] Although the SDF refers to a "carbon budget" throughout, due to the relevance of non-CO2 GHG emissions to PE sector pathways and the SDF's requirement that all sector pathways consider the effect of non-CO2 gases, we consider the budget allocation criteria with respect to all Kyoto GHG emissions rather than only CO2 emissions.

129). The fifth is carbon dioxide removal (CDR), which is the total amount of CO2 actively removed from the atmosphere through approaches that include afforestation, reforestation, bioenergy with carbon dioxide capture and storage (BECCS), and direct air capture (DAC). As much as these are indicators that may be assessed through an examination of mitigation pathways, they also represent discrete supply and demand-side changes that need to be deployed in proportional measure to keep warming below 1.5C or WB-2C according to each scenario.

Five transition characteristics

Reducing final energy demand is the preferred decarbonization lever in the eyes of the IPCC, as it is associated with reduced mitigation costs and less reliance on CDR across virtually all stringent mitigation scenarios (Rogelj, et al. 2018, 149). There is also robust evidence and high agreement that accelerating energy efficiency in all sectors is both a necessary condition for limiting warming to 1.5C and has synergies with a large number of SDGs (J. Roy 2018, 460). Likewise, stringent sector-specific policies that reduce energy demand are considered not only important, but necessary for emissions to peak by 2030 (Mejean, et al. 2019). These benefits are partly due to the fact that reduced energy consumption avoids the resource requirements and gross emissions associated with both conventional fossil fuel combustion and low/no-carbon energy generation.[7]

Electrifying energy services, decarbonizing power, and **decarbonizing non-electric fuel use in energy end-use sectors** reflect changes to the underlying final energy mix and/or deployment of carbon dioxide capture and storage (CCS) at different points of combustion. Model-scenarios with greater energy system flexibility tend to depict high rates of electrification and decarbonization of power, while less responsive model-scenarios tend to rely on high rates of CDR, in addition to decarbonization of power and non-electric fuel use (Kriegler, et al. 2015).

CDR may occur inside or outside the boundary of the energy system. In many no/low-overshoot scenarios, CDR plays a major role in compensating for residual emissions to achieve net-zero. In overshoot scenarios, CDR may also be used to reduce atmospheric CO2 once the emissions budget has been surpassed. CDR is distinct from CCS, which prevents emissions at the point of combustion from entering the atmosphere, except for the special case of BECCS. Among SR15 scenarios, BECCS and AFOLU CDR dominate total CDR, but scenarios exist for each case where they play no role at all (P. Forster 2018).[8] In a new paper, one of the coordinating lead authors of SR15 explains that the perceived linkage between late-century CDR and limiting warming to 1.5C or well-below 2C is not robust; rather, it reflects design elements underlying the present cohort of

[7] Bioenergy, for example, is associated with increased competition for land, possible land-use change emissions, and gross emissions via biomass combustion; and non-biomass renewables rely on the extraction of relatively scarce rare earth minerals. All of these uncertainties and externalities are avoided if energy use is reduced in the first place.
[8] According to the authors, this demonstrates “flexibility in substituting between individual CDR measures, once a portfolio of options becomes available.”

scenarios that strongly limit the IAM-derived solution space (Rogelj, Huppmann, et al. 2019). Figure 3 depicts the range of total CDR in SR15 scenarios (1.5C, high or low/no overshoot) compared to peak warming.

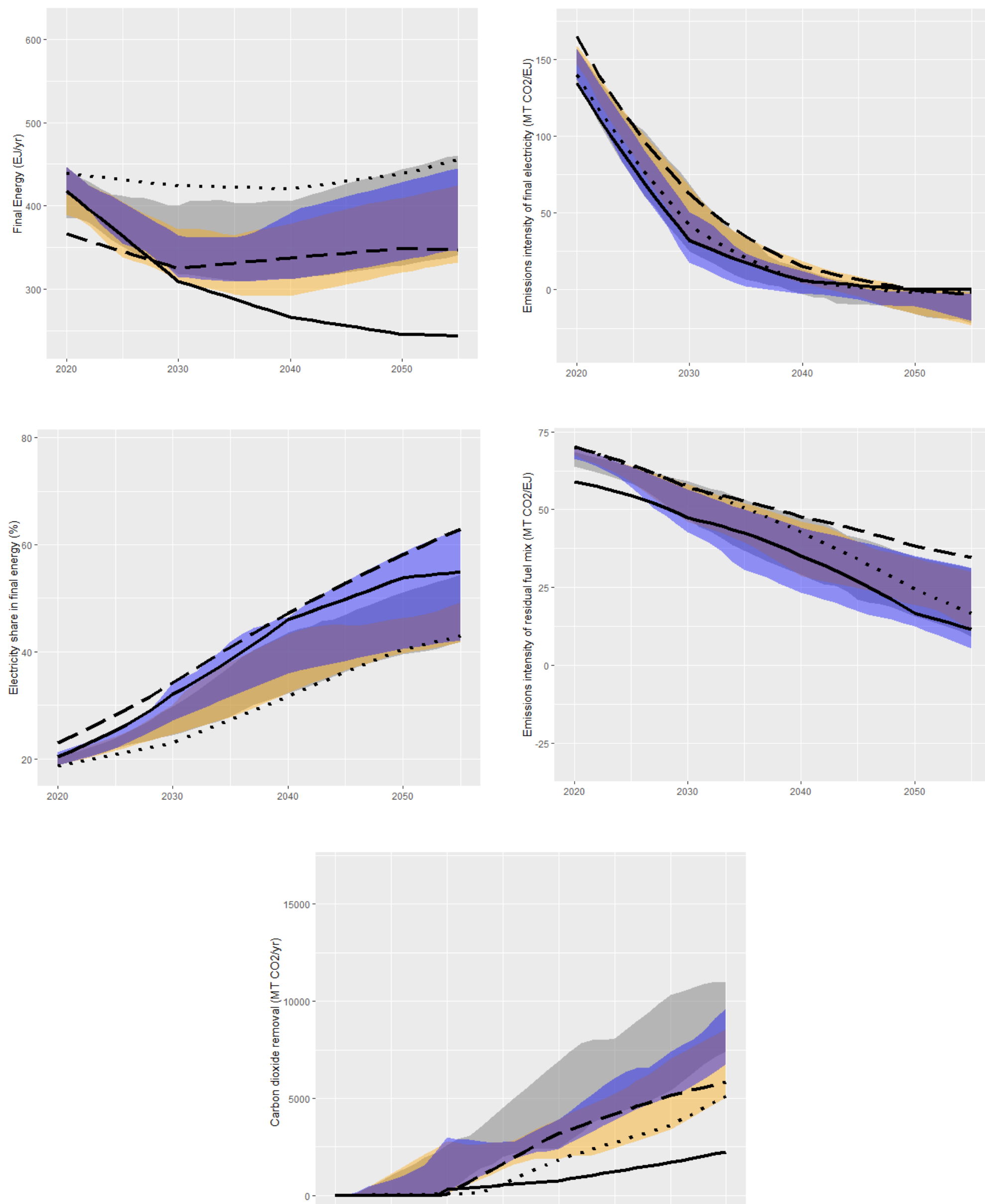


Figure 2: Five characteristics of the energy system transition across the SBTi 1.5C envelope (blue), CA 1.5C envelope (orange), low/no-overshoot 1.5C scenario envelope (grey), and archetype scenarios (black lines). The subplots show (a) final energy demand, (b) emissions intensity of final electricity, (c) the electricity share in final energy, (d) the emissions intensity of residual (non-electricity) fuel mix, and (e) carbon dioxide removal. Shaded areas for the SBTi 1.5C envelope, CA 1.5C envelope, and low/no-overshoot 1.5C scenario envelope in this plot and all successive plots are interquartile ranges.

The relative importance of each of these five characteristics is highly variable, but most clearly demonstrated by the four archetype scenarios. For example, in scenarios categorized by

improved energy efficiency and the achievement of SDGs (P2 and P1), final energy demand is reduced by X% between 2015 and 2030, which reduces the scenarios' reliance on non-electric fuel decarbonization and CDR; conversely, energy demand in P3 and P4 is increased by X% over the same timeframe, which increases the scenarios' reliance on both non-electric and electric fuel decarbonization and CDR. In the following section, PE sector-specific compliments to the five energy system transition characteristics are defined as KIs and examined in closer detail.

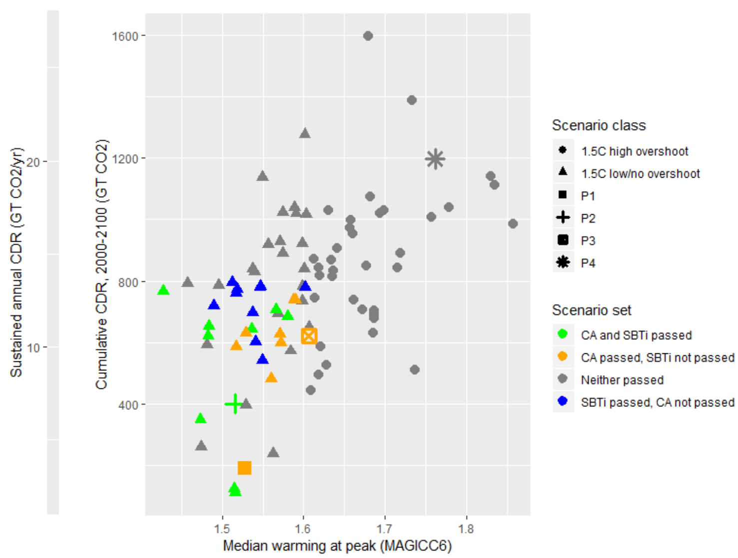


Figure 3: Cumulative CDR (GT CO2, 2000-2100) vs. peak warming in SR15 scenarios with at least a 50% chance of limiting warming in 2100 to 1.5C. Scenarios included in both the SBTi 1.5C envelope and CA 1.5C envelope are colored green, scenarios in the CA 1.5C envelope and not in the SBTi 1.5C envelope are colored orange, scenarios in the SBTi 1.5C envelope filtered out of the CA 1.5C envelope are colored purple, and all other scenarios are colored grey. Shape indicates archetype scenario or scenario class in SR15. A secondary y-axis indicates the approximate, sustained annual CDR based on annual CDR in 2070 (Supplementary Figure 1).

Box 1. Perspectives on CDR

There is widespread agreement in the scientific community that it is risky to rely on the future deployment of CDR to limit warming. Notably, the authors of SR15 specify that "most CDR technologies remain largely unproven to date and raise substantial concerns about adverse side-effects on environmental and social sustainability (Rogelj, et al. 2018)." Moreover, assessments have concluded that reliance on CDR may defer near-term ambition and the associated system changes that are needed to avoid 'carbon lock-in,' as well as overestimating our ability to manage global carbon cycle flows (Minx, et al. 2018). Strefler et al. (2018) note that in most scenarios, "if CDR is available, it is not exclusively used as a last resort, but also driven by economic reasons [leading to] a higher exploitation of the potential beyond minimum requirements," resulting in a heightened risk of climate change irreversibility. Despite these issues, many researchers believe that mitigation without CDR will not be enough and that overlooking CDR in the short-term would inhibit its scalability and effectiveness down the line.

It is well understood that if CDR is, in fact, needed to reduce atmospheric CO_2 in the future, the requisite political and technological demands would be immense; and thus, efforts to develop CDR mechanisms should begin as soon as possible. In light of these challenges, some researchers have suggested that CDR can be more usefully thought of as an "emissions offset" strategy that can be integrated into reduction efforts in the near-term, compensating for residual emissions in hard-to-mitigate sectors, but that their utility as a "climate recovery" mechanism should be avoided (Lomax and Workman 2015). Crucially, such an approach would necessitate the development of a CDR accounting and trading scheme to enable hard-to-mitigate sectors to reduce their emissions appropriately, but it would not entail reducing those sectors' mitigation burden by enlisting pathways that rely on CDR outside those sectors' boundaries.

Lastly, some researchers have questioned the social and political acceptability of CDR – which models make no attempt to resolve – noting that public opposition could inhibit the real-world deployment of CDR (Lin 2019). Their concern seems to be well-founded, as more than 110 civil society organizations – many of them representing indigenous peoples, who are among the most harmfully impacted by climate change and extractive industries – support banning all forms of CCS and placing limits on land-use related CDR proposals. Their statement cites potentially adverse effects on water and food availability, land rights, and Self Determination as primary concerns (Indigenous Environmental Network, Friends of the Earth International, La Via Campesina, Climate Justice Alliance, ETC Group, and Biofuelwatch 2018).

Social and political issues aside, Fuss et al. (2018) estimate based on a systematic review of the literature that the independent, sustainable sequestration potentials of BECCS and AR in 2050 are 0-5 GT CO_2/yr and 0-3.6 GT CO_2/yr, respectively – values that have been included in the Summary for Policymakers of SR15 and are a component of CA's Paris-aligned scenario filter.

5. Key indicators of the PE sector transition

Establishment of KIs

The PE sector plays a crucial role in the overall energy system by supplying the energy that is later transformed into energy services. In this section, KIs for the PE sector are defined in part to reflect the overall energy system characteristics introduced in Section 3, but also to assess more specific qualities of the PE sector and subsectors (i.e., PE products). Calculation methodologies for each KI are included in Supplementary Text 3.

PE consumption

The purpose of the energy system is to meet final energy demand with the appropriate supply, so it should be no surprise that total PE consumption is strongly correlated with final energy demand (Figure 4). Thus, we examine total PE consumption as a KI that is closely linked to final energy demand, which was defined as a characteristic of the energy system transition in Section 3 (Figures 2a, 5, and 9).

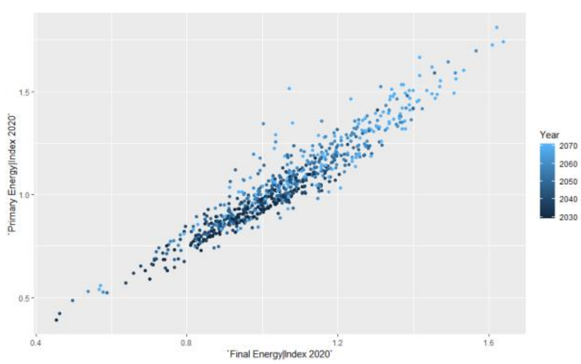


Figure 4: Final energy demand and primary energy consumption, both relative to 2020, across all 1.5C low/no-overshoot, 1.5C high-overshoot, and lower 2C scenarios in the SR15 database plotted for the years 2030, 2040, 2050, 2060, and 2070 (years indicated by color).

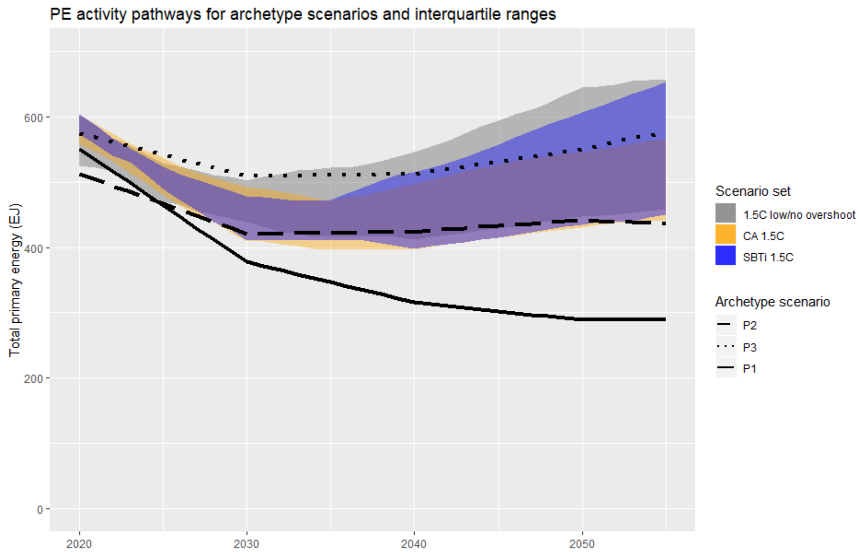


Figure 5: PE consumption across the SBTi 1.5C envelope (blue), CA 1.5C envelope (orange), low/no-overshoot 1.5C scenario envelope (grey), and archetype scenarios (black lines).

PE-related emissions and PE emissions intensity

PE-related emissions and PE emissions intensity are identified as KIs that reflect underlying, energy-related GHG "budgets" across scenarios, and how energy-related budgets are preserved according to each scenario's PE activity pathway (Figures 6, 7, and 9). (Note than in SR15 IAMs, energy-related GHG budgets are generally not fixed, as such, because AFOLU and industrial process-related emissions are also dynamically computed.)

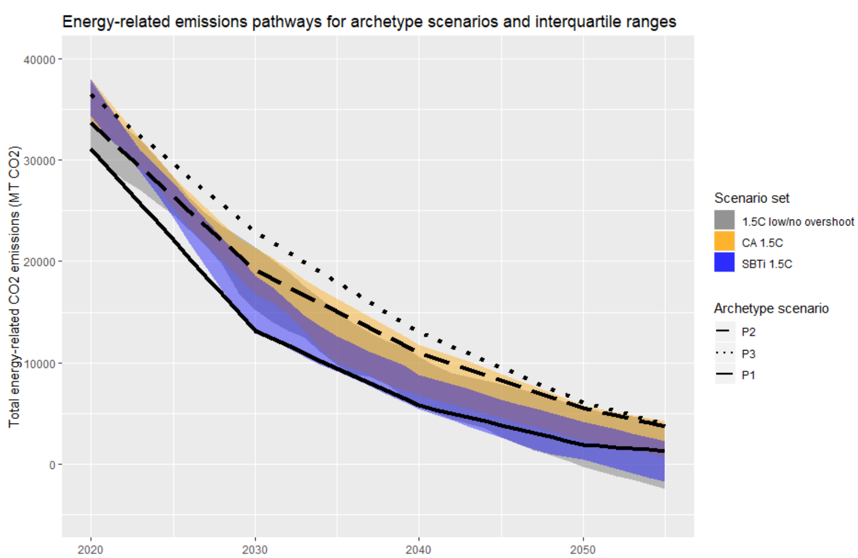


Figure 6: PE-related emissions across the SBTi 1.5C envelope (blue), CA 1.5C envelope (orange), low/no-overshoot 1.5C scenario envelope (grey), and archetype scenarios (black lines).

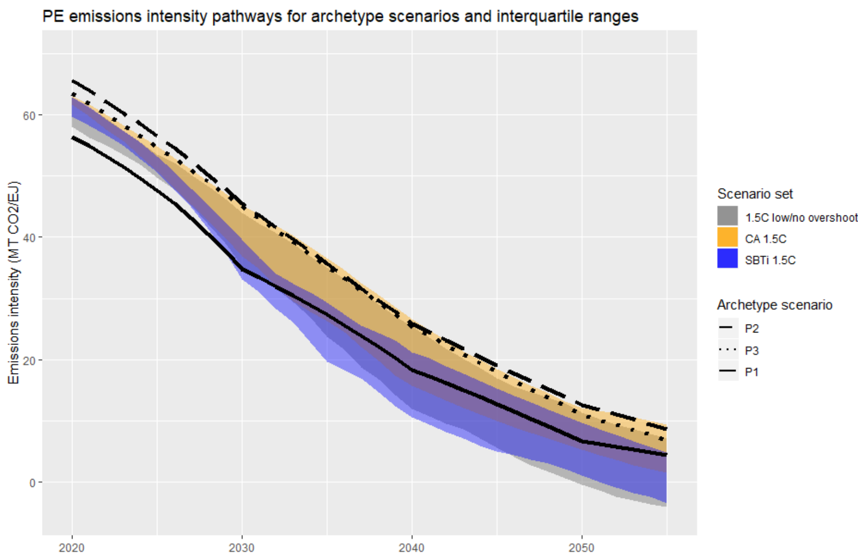


Figure 7: PE emissions intensity across the SBTi 1.5C envelope (blue), CA 1.5C envelope (orange), low/no-overshoot 1.5C scenario envelope (grey), and archetype scenarios (black lines).

CDR

Many scenarios rely on CDR to reduce atmospheric concentrations of CO2, thus increasing the amount of CO2 that may be emitted elsewhere in the economy. Within the context of a PE sector SBT-setting methodology, it is critical to interrogate the relationship between PE sector and product pathways and the scenario's reliance on CDR (Figure 10), due to the fact that CDR is unproven at the scale required in many 1.5C scenarios and may adversely affect near-term ambition.

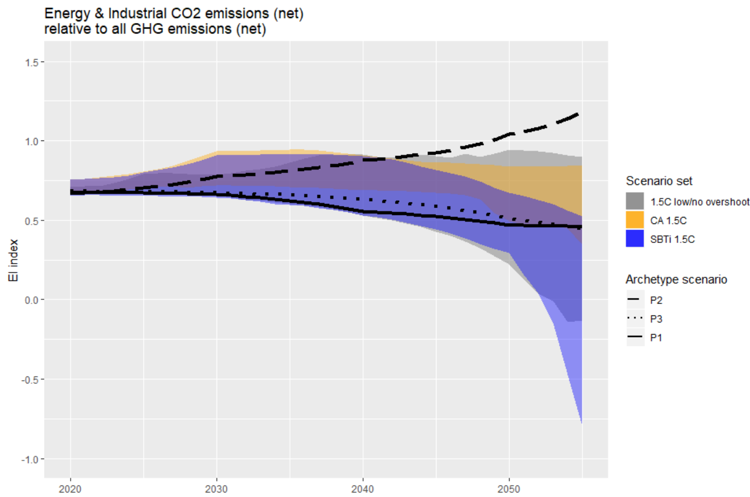


Figure 8: EI Index across the SBTi 1.5C envelope (blue), CA 1.5C envelope (orange), low/no-overshoot 1.5C scenario envelope (grey), and archetype scenarios (black lines).

EI Index

By design, IAMs calculate the “least discounted cost” solution to achieve a prescribed goal within the constraints imposed by the experiment. The constraints, however, are intentionally modified by researchers, which has a significant impact on the qualities of each solution (see Box 2). In order to assess the compliance of 1.5C-aligned PE sector pathways with the SDF, it is important to examine the relative contribution of the PE sector to total emissions mitigation. The KI EI Index, which is defined as the scenario’s total Energy and Industrial Process-related CO2 emissions divided by the absolute value of total GHG emissions calculated each year, is used to examine the PE sector emissions allocation relative to the global emissions pathway (Figure 8). EI Index shows the relative mitigation burden allocated to energy and industrial CO2 emissions compared to the global emissions pathway.

PE sector-wide results

All scenarios require very large emissions reductions between 2020 and 2035 (Figure 6), which are achieved through a combination of reduced PE consumption and PE intensity (Figures 5 and 7). In the SBTi 1.5C set, median PE consumption is reduced by 25% and median PE intensity is reduced by 59%, consistent with a median 70% reduction of annual PE-related emissions (4.7% linear annual reduction). By comparison, the P1 archetype, which achieves an equivalent PE-related emissions reduction, relies more on reduced PE consumption than intensity, which are reduced by 37% and 52%, respectively, over the same time period. In the 1.5C low/no overshoot set, median PE consumption is reduced by 18% and median PE intensity is reduced by 53%, consistent with a median 62% reduction in annual, PE-related emissions. These reductions are most similar to the P2 archetype, which achieves a 56% reduction in annual, PE-related emissions through an 18% reduction in PE consumption and 45% reduction in PE intensity. The P3 archetype achieves a similar reduction in PE intensity (46%) but does not reduce PE consumption

as much (11%), resulting in an emissions reduction of only 51% between 2020 and 2035. Accordingly, P3 relies on almost three times as much CDR as P1 and 50% more CDR than the P2 archetype. The CA 1.5C envelope PE consumption pathway falls between those of P2 and P3, while its emissions and intensity pathways are between those of P1 and P3. It is similar to the SBTi 1.5C envelope, differing mainly in its depiction of PE consumption between 2040 and 2060 (showing a narrower range that does not increase consumption as much), as well as in its depiction of a more gradual reduction in emissions and emissions intensity.

PE product-specific results

There is a much greater amount of variation among PE product-specific pathways than sector-wide pathways because each scenario entails a different vision of how its limited, PE sector emissions budget is allocated among PE products and to which PE products CCS is applied, if at all. Accordingly, product-specific pathways from multiple scenarios should not be combined because total emissions and/or total PE would be inconsistent with the geophysical and sociopolitical bounds of any scenario. In the following paragraphs, each fossil fuel product is examined through the lens of KIs separately and in Section 5, relationships between product-specific pathways are examined in more detail.

Oil

Oil-related emissions and oil consumption vary widely among scenarios; however, in most scenarios, the emissions intensity of oil hardly changes at all. This is most likely due to the fact that many transportation fuels are derived from oil, and it would be far more expensive to capture the combustion-related emissions at each vehicle than to capture the emissions of other PE products like biomass, coal, and gas that are usually combusted at power plants or in large-scale industrial processes.

In the SBTi 1.5C and CA 1.5C sets, median oil-related emissions and consumption are reduced by about 50% between 2020 and 2035, while in the 1.5C low/no-overshoot set, median oil-related emissions and consumption are reduced by 40% between 2020 and 2035, each with a standard deviation of 10-20%. In the P1 scenario, oil-related emissions are reduced by 60% between 2020 and 2035, while in the P2 and P3 scenarios, oil-related emissions are reduced by around 35%.

Gas

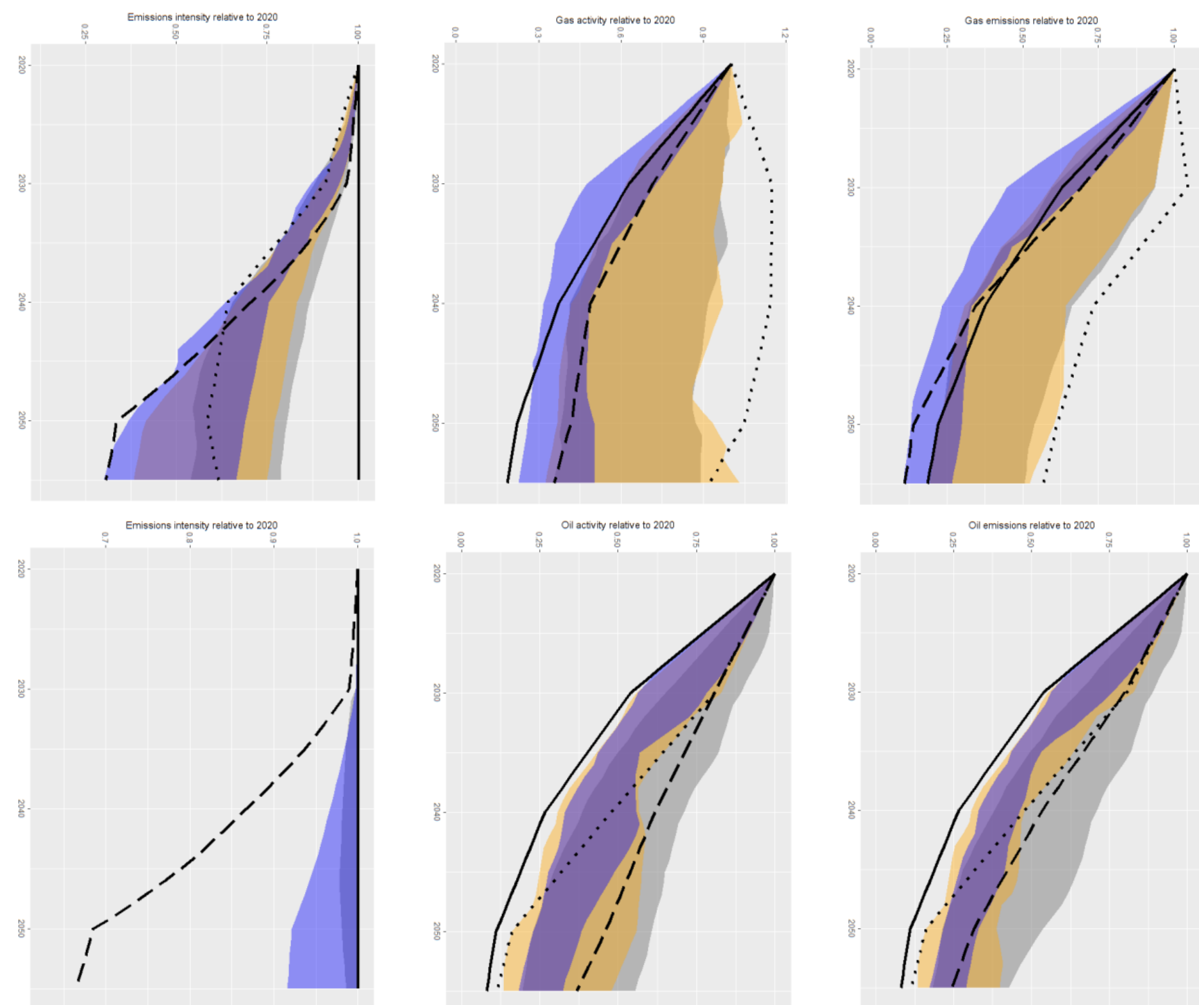
The role of natural gas in the energy sector transition also varies substantially. In the SBTi 1.5C set, median gas-related emissions decreases by 61% between 2020 and 2035, while in the CA 1.5C set and low/no-overshoot sets, median gas-related emissions decrease by 50% and 40%, respectively. By comparison, in P1 and P2, gas-related emissions are reduced by about 50%, but in P3 gas-related emissions is only reduced by 11%.

Gas consumption varies even more widely than gas-related emissions: in each scenario envelope, the change in consumption between 2020 and 2035 is characterized by at least a 30% standard deviation. In P1, gas consumption decreases by 50% between 2020 and 2035, while in P3, gas consumption increases by 15% -- in part to replace oil and coal, which are reduced in

larger proportion compared to gas in P3 than in P1 and P2. The change in gas's emissions intensity between 2020 and 2035 does not vary as widely among scenarios, but the range of intensities grows between 2035 and 2050 as CCS-equipped gas combustion must be scaled up in scenarios that continue to rely on gas as a major source of PE.

Coal

In all three scenario sets, total coal-related emissions and coal related energy consumption are drastically reduced between 2020 and 2035; however, the emissions intensity of coal varies widely among scenarios, reflecting different interpretations of coal's long-term viability as a PE product. For example, in the P3 archetype, the emissions intensity of coal approaches zero and it continues to be used as a PE product throughout the century, while in the P1 archetype, coal is gradually phased out entirely, so its emissions intensity matters less and the investment that would have gone toward CCS-equipped coal is spent to mitigate emissions elsewhere.



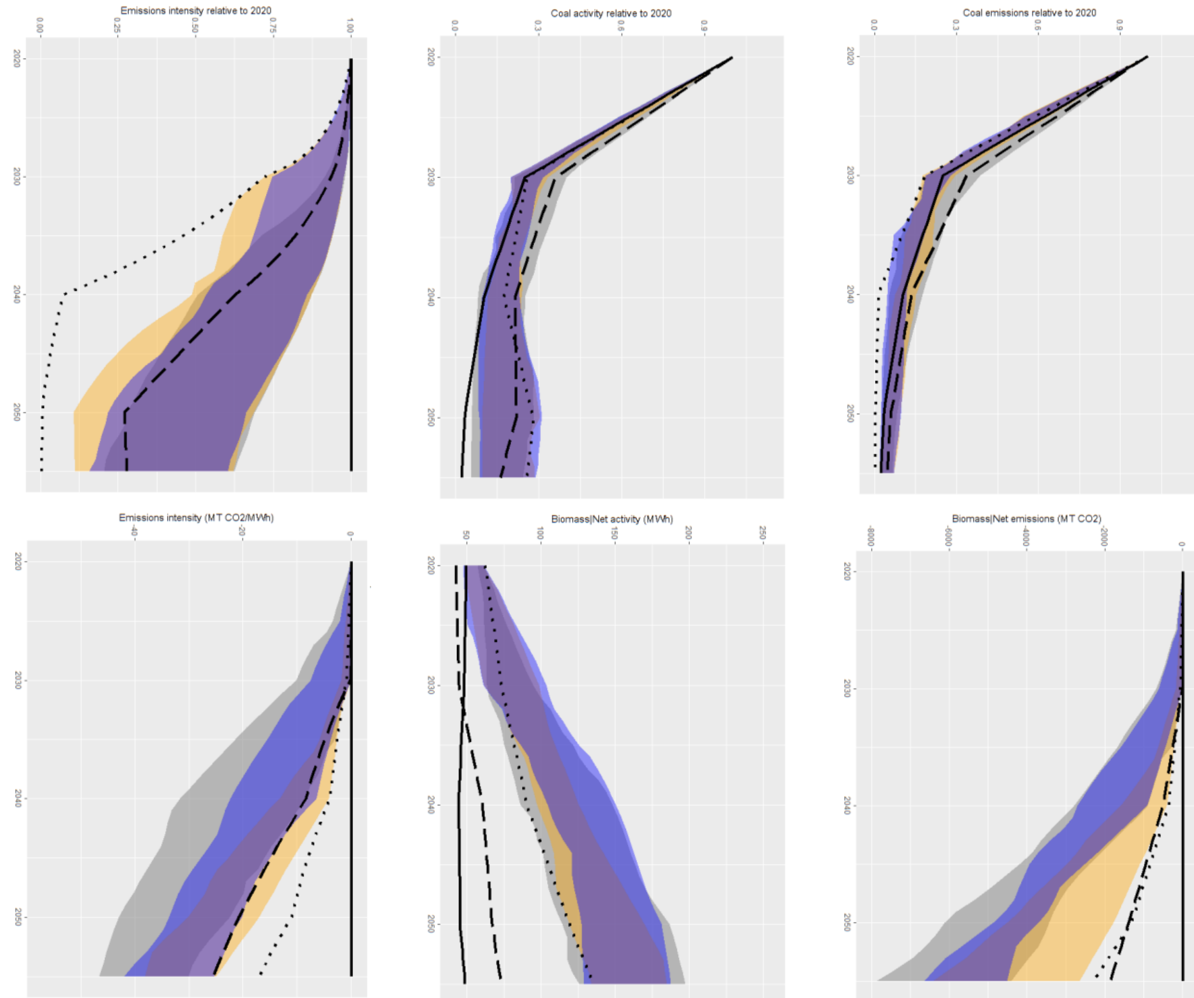


Figure 9: PE product consumption, product-level emissions, and intensity for gas, oil, coal, and biomass across the SBTi 1.5C envelope (blue), CA 1.5C envelope (orange), low/no-overshoot 1.5C scenario envelope (grey), and archetype scenarios (black lines). P1 is the solid black line, P2 is the dashed line, P3 is the dash-dotted line, and S4 is the dotted line.

Biomass

In most scenarios, bioenergy both replaces fossil energy and contributes to CDR through the partial application of BECCS. The total availability of biomass for energy production is usually limited by land availability and land-use competition with other critical services (e.g., crop production, AR); while the proportion of bioenergy that is equipped with CCS is highly dependent on the energy services provided by biomass in each scenario. For example, in some scenarios, liquid biofuels are an important factor in reducing oil consumption, despite the fact that liquid biofuels, similarly to oil, have very low CCS rates; whereas in other scenarios, biomass is primarily used for power generation with high CCS rates (Bauer, et al. 2018). Accordingly, not only does total bioenergy consumption vary greatly among scenarios, but its “sequestration” and “sequestration intensity” (defined as the inverse of emissions and emissions intensity) are also highly variable in ways that are linked to each scenario’s fossil PE product pathways.

In all three scenario sets, biomass PE consumption increases steadily yet rapidly between 2020 and 2030, reaching about 100 MWh in 2035. In P2 and P3, biomass PE consumption increases more slowly reaching 53 and 82 MWh in 2035, respectively, while in P1, biomass PE consumption never exceeds 50 MWh. Biomass PE consumption continues to increase at similar rates between 2035 and 2060 in all three scenario sets; although it increases more slowly in P2 and P3.

Bioenergy CO2 sequestration is highly variable across scenarios. In the SBTi 1.5C scenario set, median bioenergy CO2 sequestration in 2035 is 610 MT with a standard deviation of 930 MT, while in the low/no-overshoot set, median bioenergy CO2 sequestration is similar (630 MT), but the standard deviation is nearly double (1800 MT CO2). Neither of these scenario sets limit reliance on BECCS. By comparison, the CA 1.5C scenario set, which excludes scenarios with very high BECCS in 2050, has a median of 490 MT and standard deviation of 540 MT of bioenergy CO2 sequestration in 2035. All three archetype scenarios considered here depict significantly lower bioenergy CO2 sequestration than the scenario set medians: P1, P2, and P3 depict 0 MT, 220 MT, and 260 MT of CO2 sequestration, respectively.

Similarly, the scenario set sequestration intensities vary substantially and their median intensities tend to be higher than those of the archetypes, except for the CA 1.5C set, which has a median intensity in 2035 similar to that of P2 (4.8 and 4.9 MT CO2/MWh, respectively). P3 has a lower sequestration intensity of 2.6 MT CO2/MWh, while P1 has a sequestration intensity of 0 MT CO2/MWh. This indicates that although P2 includes less bioenergy than P3, a higher proportion of it is captured, leading both archetypes to similar bioenergy CO2 sequestration pathways.

CDR results

The amount of CDR varies substantially across scenarios included in the SBTi 1.5C and/or CA 1.5C sets, ranging from about 100 to 800 GT CO2 cumulatively between 2000 and 2100 (equivalent to the sustained removal of about 0 to 15 GT CO2/year after 2070) (Figure 3). In some low/no overshoot scenarios, high rates of CDR outside the boundary of the PE system (e.g., AR) may lead to slower reductions in PE-related emissions; while in other scenarios, high rates of CDR within the boundary of the PE system (e.g., BECCS) correspond to greater reductions in total PE-related emissions. To an extent that is not assessed here, high rates of CDR in some scenarios may reflect the impact of carbon pricing on land use outside the intended scope of the experiment.[9] Regardless, AR-related CDR is always reflected by estimates of peak and end-of-century warming that are used to classify scenarios in the SR15 database, which strongly limits the relevance of SR15 temperature classifications for many analyses. For these reasons – namely, that in some experiments, including those that underlie the archetype scenarios, AR-related CDR has the capability to compensate for increased emissions within the PE system; and that in some scenarios, inadvertently high AR-related CDR negatively influences the temperature

[9] For example, the EMF33 experiment imposes budget constraints on cumulative CO2 emissions from the energy and industry sectors (including CDR by BECCS); and although AR is calculated concurrently, it does not contribute to “solving” the budget (Bauer, et al. 2018, 4).

classification of scenario – it is critical to examine both total PE-related emissions pathways and PE product emissions pathways as they relate to total CDR.

For scenarios included in the SBTi 1.5C and/or CA 1.5C set, Figure 10 shows the emissions reduction associated with each fossil PE product in 2025, 2035, and 2045. The scenarios are colored according to CDR in 2070: all but four of the scenarios depict the removal of at least 7.2 GT CO2/year by 2070 and most depict the removal of at least 10.8 GT CO2/year by 2070. Scenarios that limit annual CDR to 7.2 GT CO2/year or less are relatively closely grouped together, despite originating from three different models and experimental frameworks. Two of the four scenarios are also archetypes (P1 and P2). In addition, a significant number of scenarios with 7.2-14.4 GT CDR/year fall within the same range of PE product emissions reductions as the scenarios with 7.2 GT CDR/year or less, although the total range of PE product pathways associated with 7.2-14.4 GT CDR/year scenarios is much more variable.

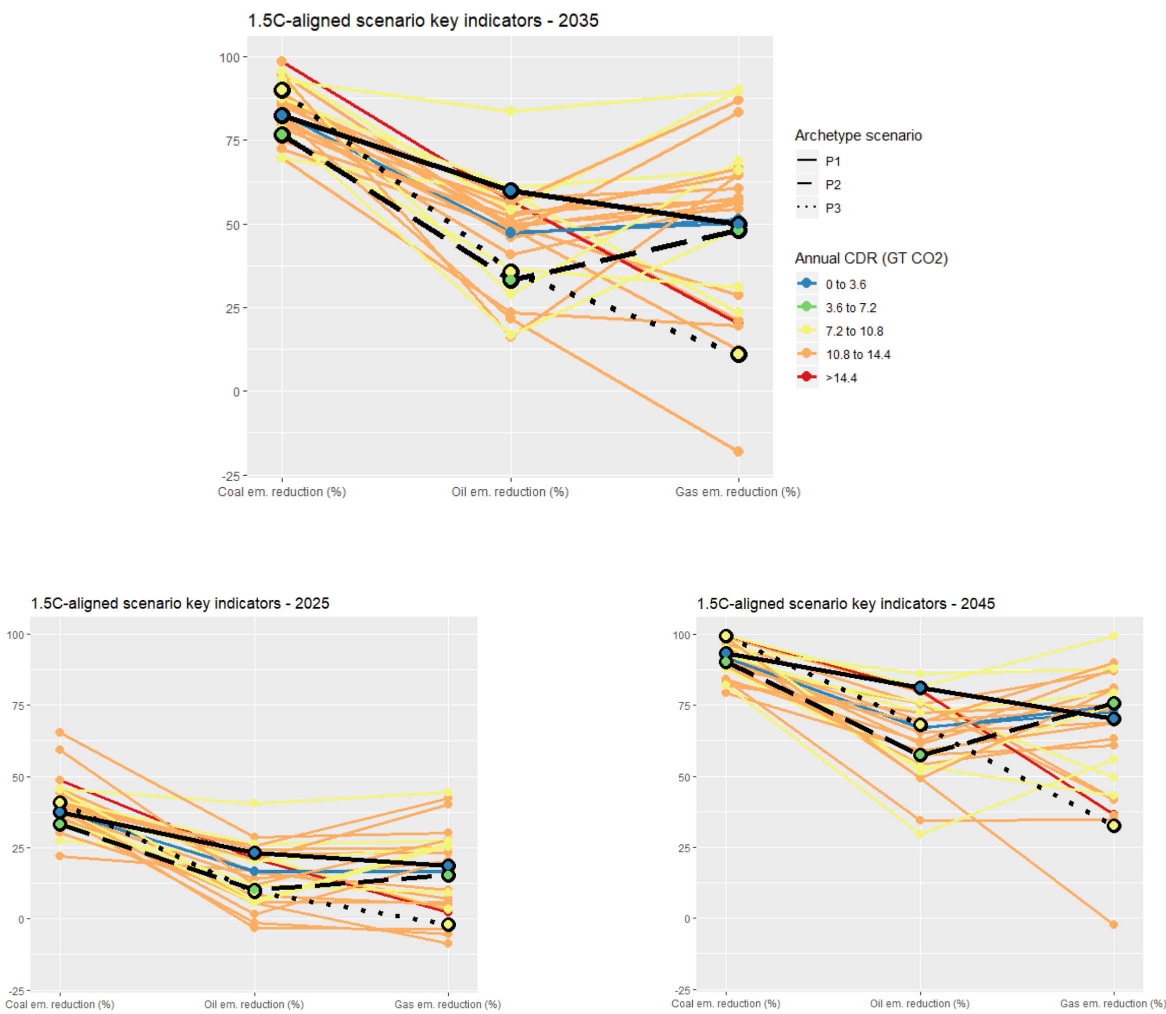


Figure 10: Emissions reductions associated with each fossil PE product (coal, gas, oil) in scenarios that have been included in the SBTi 1.5C set or CA 1.5C set, grouped by annual CDR in 2070 (color) with archetype scenarios

shown in black. Emissions reductions are shown as % reductions from 2020 levels in 2025 (bottom left), 2035 (top center), and 2045 (bottom right).

Scenarios with less than 7.2 GT CDR/year depict rapid emissions reductions for all fossil PE products that fall between the reductions specified by P1 and P2. Between 2020 and 2025, coal-related emissions are reduced by 30-40%, gas-related emissions are reduced by 20%, and oil-related emissions are reduced by 10-25%. Between 2020 and 2035, coal emissions are reduced by 75-85%, gas emissions by 50%, and oil emissions by 35-60%. By 2045, coal emissions must be about 90% lower than 2020 levels, gas emissions must be about 75% lower than 2020 levels, and oil emissions must be about 60-80% below 2020 levels.

EI Index results

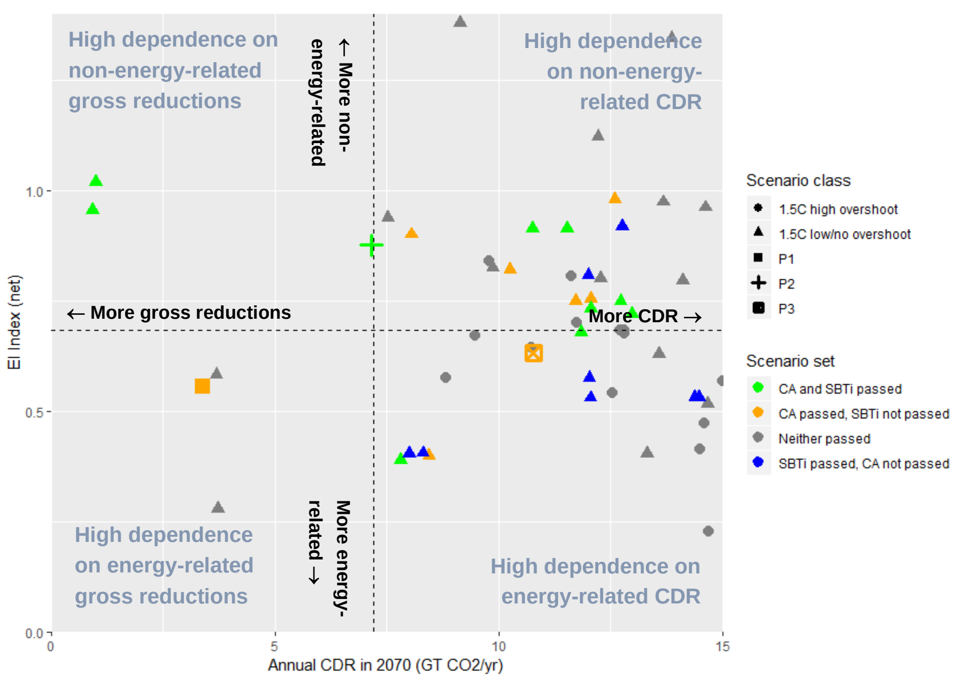


Figure 11: EI Index in 2040 vs Annual CDR in 2070. Chart is divided into quadrants where the vertical line demarcates scenarios with over/under 7.2 GT CO2/year and the horizontal line demarcates scenarios with EI Indices over/under the 1.5C low/no-overshoot median. Scenarios with >15 GT CDR/yr are not shown. The same plot with EI Index calculated as a mean anomaly from the median in years 2030, 2040, and 2050 with all Model-Scenarios labeled is included in Supplementary Figure 2.

In all three scenario sets, median EI Index increases slightly from about 0.7 in 2020 to 0.75 in 2035, where it reaches a peak before decreasing through 2050 (Figure 8, Supplementary Table 4). In 2050, the median EI Index is 0.54, 0.61, and 0.50 in the SBTi, CA, and 1.5C low/no overshoot sets, respectively. The median EI index and interquartile range in 2050 are probably higher in the CA set than in the SBTi set in part due to constrained BECCS, which may make more land available for AR-related sequestration and limit the net energy-related reductions that are achieved. The archetypes P1 and P3, which incorporate "middle of the road" socioeconomic

assumptions, depict an EI Index reducing from about 0.7 to 0.5 between 2030 and 2050, while P2 depicts a steadily increasing EI Index over the same period because heightened environmental awareness results in more ambitious mitigation across the entire land-use system.

Figure 11 demonstrates a framework that may be used to classify scenarios based on their EI Index and reliance on sustained CDR; effectively enabling the selection of scenarios that fulfill sectoral allocation requirements, as specified by the SDF, and limits on CDR, which should be informed by the technical, governance, and sustainability risks described in Box 1. In the example shown by Figure 11, appropriate scenarios would be those in the bottom left quadrant (also passing any other relevant criteria) because they demonstrate that the carbon budget is not under-allocated to energy, relative to other not covered sectors, and they constrain total reliance on CDR that is needed to limit warming in 2100. Adjusting the “threshold values” for EI Index and CDR, would affect the final set of passing scenarios. Alternatively, a specific range of values (i.e., bounded area of the plot) may be chosen, which would mainly differ by eliminating scenarios where either gross reductions, as opposed to CDR, or energy-related contributions to mitigation, as opposed to non-energy-related contributions, are too high.

6. Key indicators of the power sector transition

Establishment of KIs

The power sector plays a crucial role in decarbonizing the global economy. A significant and growing fraction of final energy demand is met by purchased electricity (Figure 2c), so efficiency improvements in electricity generation and delivery underly the emissions reductions of many other actors. Moreover, the power sector is especially capable of steep emissions reductions due to its compatibility with renewable energy sources like solar, wind, and hydro, as well as opportunities to substitute fossil energy with bioenergy with or without CCS. Calculation methodologies for each KI are included in Supplementary Text 3.

Electricity production and consumption

Gross electricity production and final electricity consumption are identified as KIs that reflect the rapid electrification of energy services, even as total final energy demand and primary energy consumption experience reduced or negative growth. Gross electricity production (Figure 12) includes the electricity that is lost to transmission and distribution, whereas final electricity consumption (Figure 2a) excludes these losses, instead capturing the total electricity delivered to end-users. The variables are closely correlated, and both are appropriate for most comparative analyses of IAM pathways; however, the specific pathways may be relevant to different subsectors of the power sector for practical target-setting purposes.

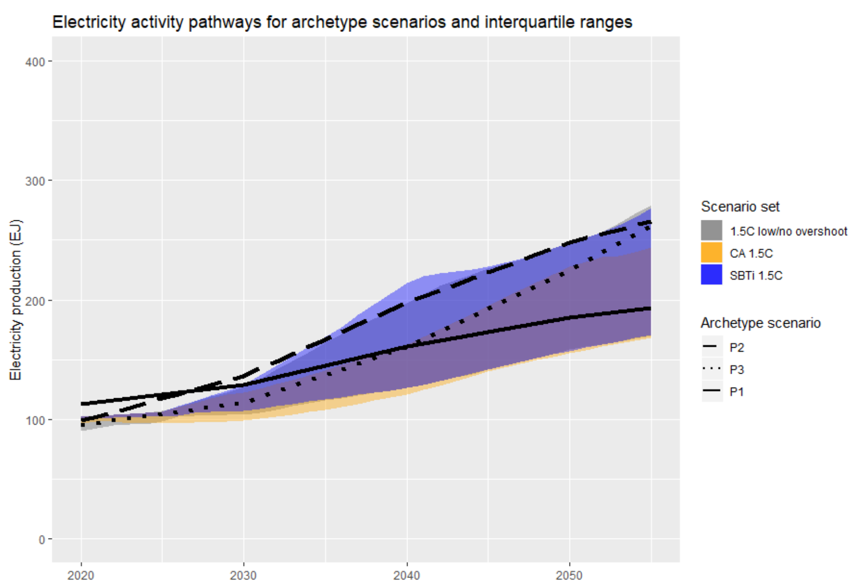


Figure 12: Electricity production across the SBTi 1.5C envelope (blue), CA 1.5C envelope (orange), low/no-overshoot 1.5C scenario envelope (grey), and archetype scenarios (black lines). The KI Electricity consumption is shown in Figure 2a.

Electricity-related emissions and emissions intensity

Electricity-related emissions and emissions intensity are KIs that demonstrate the power sector's capability and need to rapidly reduce emissions (Figures 13 and 14). Different models and

scenarios depict a wide range of approaches to achieving these reductions, but they reflect a similar conclusion: that decarbonizing electricity as fast as possible, while continuing to meet increasing demand, is among the most cost-effective levers available for the global economy to limit warming to 1.5C. Annual CDR due to BECCS in the power sector is included in these pathways.

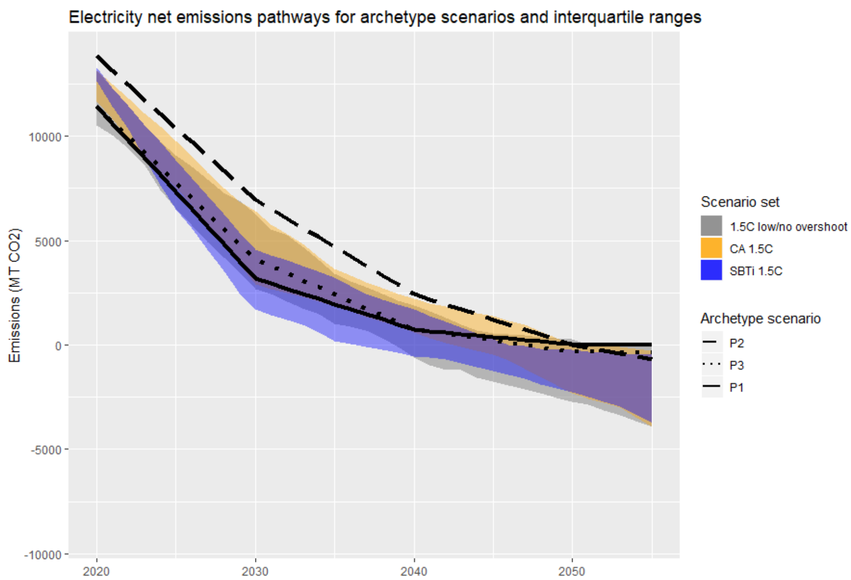


Figure 13: Electricity-related emissions across the SBTi 1.5C envelope (blue), CA 1.5C envelope (orange), low/no-overshoot 1.5C scenario envelope (grey), and archetype scenarios (black lines).

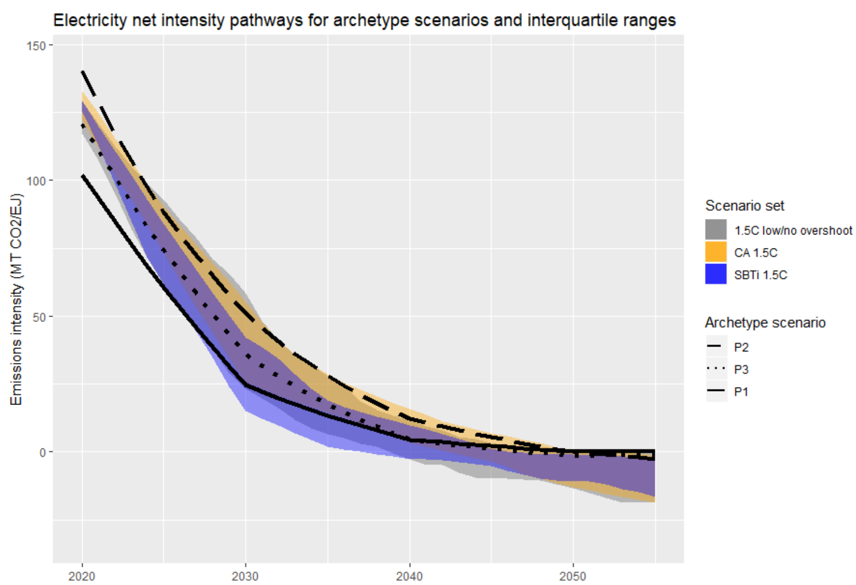


Figure 14: Emissions intensity of electricity production across the SBTi 1.5C envelope (blue), CA 1.5C envelope (orange), low/no-overshoot 1.5C scenario envelope (grey), and archetype scenarios (black lines).

BECCS and Total CDR

Many scenarios rely on CDR to reduce atmospheric concentrations of CO2, thus increasing the amount of CO2 that may be emitted elsewhere. Aside from afforestation/reforestation in the land-use sector, the power sector is the only large-scale provider of CDR in most scenarios, which is achieved through BECCS.[10] It is important to understand how scenarios' overall reliance on CDR, as well as the amount of CDR achieved by the power sector, affects sectoral emissions pathways and intersectoral contingencies (i.e., budget allocation among sectors). Total CDR and BECCS as a percentage of total CDR are examined as KIs in Figure 15.

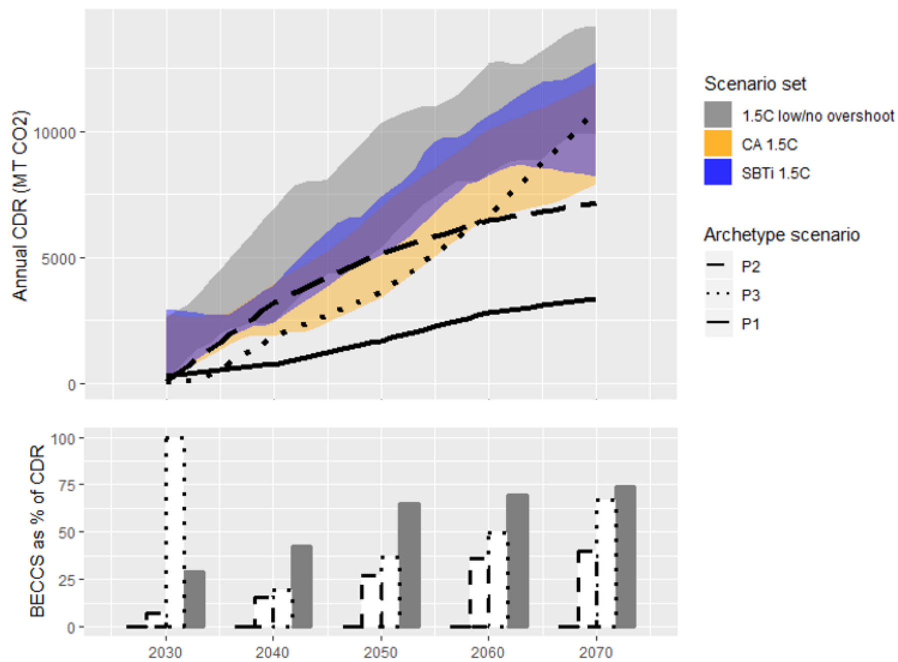


Figure 15: Total CDR (top) is shown across the SBTi 1.5C envelope (blue), CA 1.5C envelope (orange), low/no-overshoot 1.5C scenario envelope (grey), and archetype scenarios (black lines). BECCS as a percentage of total CDR (bottom) is shown for the archetype scenarios and the 1.5C low/no overshoot envelope. BECCS as a percentage of total CDR in the CA 1.5C and SBTi 1.5C envelopes (not shown) is similar to that of the 1.5C low/no overshoot envelope.

P Index

The KI P Index, which is defined as a scenario's total electricity-related CO2 emissions divided by the absolute value of total GHG emissions calculated each year, is used to examine the power sector emissions allocation relative to the global emissions pathway (Figure 16). The power sector's emissions allocation in part reflects its presumed deployment of BECCS, as well as the scenario's reliance on land sector emissions reductions and removals. For example, P Index is

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[10] In some models, CDR may also be achieved by direct air capture or the application of BECCS to the production of liquid hydrogen fuels.

generally lower in scenarios that rely on BECCS because removals in the power sector allow other sectors to reduce their own emissions more slowly, and P Index is higher in scenarios with ambitious land sector transformations because the energy system emissions budget is increased and/or the power sector's requisite deployment of CDR is reduced.

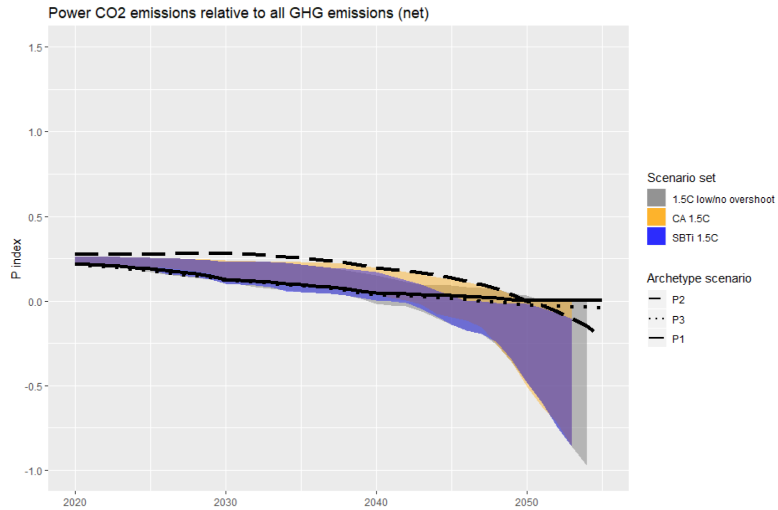

Figure 16: P Index across the SBTi 1.5C envelope (blue), CA 1.5C envelope (orange), low/no-overshoot 1.5C scenario envelope (grey), and archetype scenarios (black lines).

Power sector results

All scenarios require very large emissions reductions in the power sector between 2020 and 2035 (Figure 13), which are achieved through steep reductions in the emissions intensity of electricity, while electricity production continues to rise (Figures 12 and 14). In the SBTi 1.5C set, median power sector production is increased by 38% and median intensity is reduced by 88%, consistent with a median 83% reduction of annual electricity-related emissions (5.5% linear annual reduction). Similarly, the P1 and P3 archetypes are characterized by steep intensity reductions (85-87%) and emissions reductions (79-83%) between 2020 and 2035, while P2 reduces its electricity-related intensity and emissions less, by 80% and 66%, respectively.

Although the emissions pathways of P1 and P3 are within the interquartile range of all three scenario sets between 2020 and 2035, net electricity-related emissions in the scenario sets continue to decline, transforming the sector into a net CO2 sink by around 2045, whereas in P1 and P3, electricity-related emissions appear to level out around 0 GT CO2/yr in 2045.

BECCS and total CDR results

The broad similarities that are observed across scenarios' power sector emissions and intensity pathways conceal a high degree of variability in how power sector transformations are achieved. In the SBTi 1.5C and 1.5C low/no overshoot sets, CDR increases from around 0 GT CO2/yr to a median of 3-4 GT CO2/yr comprised of about 30% BECCS between 2030 and 2040 and reaches about 9-10 GT CO2/yr comprised of about 70% BECCS by 2060 (Figure 15). These pathways indicate that in the SBTi 1.5C and 1.5C low/no overshoot sets substantial BECCS deployment is required to partially compensate for residual emissions due to fossil-related electricity generation

before net-zero is achieved within the sector. Likewise, Figure 9 illustrates that the SBTi 1.5C and 1.5C low/no overshoot sets are characterized by steadily increasing biomass-related primary energy between 2020 and 2050, with BECCS introduced at scale around 2030. By contrast, P1 achieves a similar power sector emissions reduction without relying on BECCS at all, instead requiring fossil electricity generation to be phased out more quickly. P2 and P3 do not exclude BECCS, but they rely on it less than all three scenario sets.

P Index results

P2 is characterized by substantially higher rates of CDR in the land sector than P1 or P3, explaining why electricity-related emissions in P2 are not reduced as much between 2020 and 2035. Likewise, more rapid net emissions reductions in the power sector are reflected by a steadily reducing P Index in P1 and P3, while P Index stays relatively constant in P2 (Figure 16). Despite large differences in each scenario's balance between gross reductions and CDR, P1 and P3 rely on a similar contribution from the power sector between 2030 and 2050, while P2 relies more on mitigation outside the power sector (Figure 17).

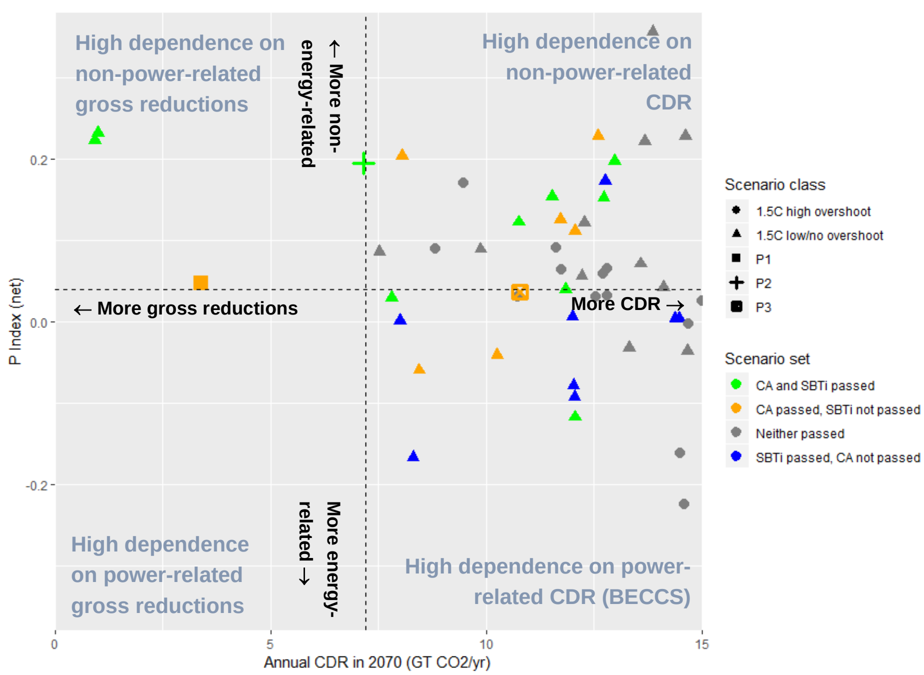

Figure 17: P Index in 2040 vs Annual CDR in 2070. Chart is divided into quadrants where the vertical line demarcates scenarios with over/under 7.2 GT CO2/year and the horizontal line demarcates scenarios with EI Indices over/under the 1.5C low/no-overshoot median. Scenarios with >15 GT CDR/yr are not shown. The same plot with EI Index calculated both in 2040 and 2050 with all Model-Scenarios labeled is included in Supplementary Figure 2.

7. Discussion

The previous section provided an overview of how scenarios included in the SR15 database depict a wide range of energy system transitions, as well as demonstrating some of the relationships between KIs that affect the pace and allocation of different energy system transitions. In this section, the aggregate analyses shown above are more thoroughly contextualized by an examination of associated academic literature, which includes a variety of experimental frameworks and model-specific considerations. Additionally, this section includes recommendations for defining Paris-aligned pathways that are consistent with the principles of the SBTi and address new challenges related to the achievement of "net-zero" emissions.

Box 2. Interpreting variability across PE system pathways

Model influence

Different modeling frameworks utilize a wide range of representations of the global energy system and its relationships to the economy and land use; and generate scenarios according to mathematically distinct solution methods. Some research projects (i.e., multimodel studies) apply the same experimental conditions and constraints to a variety of different models, which enables researchers to identify robust conclusions, as well as to assess and interpret inter-model variability. By considering the specific characteristics of each model alongside its respective solution to the same "question," researchers can derive an in-depth understanding of results that may seem divergent at first. For example, "high response" models such as MESSAGE are characterized by greater flexibility of the primary energy mix paired with a tendency to rely more on the reduced carbon intensity of energy to limit emissions compared to "low response" models such as WITCH that are characterized by a less flexible energy mix and a tendency to rely more on reduced energy intensity relative to economic growth (Kriegler, et al. 2015). These behavioral tendencies are not explicitly programmed into models, but they have been identified by extensive diagnostic testing and should be taken advantage of to improve understanding.

Experimental influence

The SR15 scenario database captures 411 different scenarios from four multimodel studies and twelve single-model studies (P. Forster 2018). Similarly to the preceding assessments in this whitepaper, SR15 assesses the results of many different models and experiments in order to identify robust conclusions (i.e., those that are consistently reached for a given category of scenario) and to identify those that reflect greater variability. Greater variability should not be conflated with poor understanding because variability across the SR15 database emerges, in part, from the fact that experiments are intentionally designed to test various "boundary" conditions – feasible and infeasible, preferable and not preferable. For example, it is common for experiments to compare scenarios where mitigation begins immediately to those where increased ambition is delayed until 2030 or where certain technologies are fully available vs. omitted entirely (Vrontisi and et al. 2018) (Bauer, et al. 2018).

Additionally, emissions budget constraints vary considerably among experiments. For example, some experiments only constrain energy and industrial-process related emissions; and some

experiments only constrain CO_2 emissions. Regardless of budget constraint, land-use related emissions and non-CO_2 emissions are always computed by scenarios included in the SR15 database, but they may be calculated in a way that is *consistent* with transformations resolved by the intended scope of the model, rather than explicitly as part of the solution. For example, some POLES scenarios in the EMF33 experiment, which only constrains energy and industrial-process related CO_2 budgets, depict a rapid, 300% reduction of AFOLU-related emissions between 2020 and 2025 as a consequence of high carbon pricing that is required to limit energy and industrial process-related CO_2 emissions appropriately. These scenarios should not be interpreted as suggesting that a 300% reduction in AFOLU-related emissions is part of the model's solution to preserving the experimental budget.

In section 7, four experiments that yield important insights into PE sector transformations are considered.

Examining the experimental context

Scenarios towards limiting temperature increase below 1.5°C (Rogelj and et al. 2018)

The SSP scenario framework was established to illustrate different mitigation pathways that are consistent with clear, socioeconomic narratives. Three of the five SSPs are summarized in Table 1 (SSP1: P2, SSP2: P3, and SSP5: P4), while the remaining two SSPs (SSP3 and SSP4) are excluded from this assessment due to their intentionally unfavorable narratives (e.g., increasing conflict and inequality), which also limit their potential to limit warming to 1.5C. The SSP modeling framework has been used to generate both mitigation scenarios (i.e., scenarios that limit warming to a certain level) and baseline scenarios that do not limit warming, but which express the impact of each SSP's respective assumptions as "autonomous" dynamics. For example, in the SSP1 baseline scenario, the non-fossil share of PE increases due to society's growing respect for perceived environmental boundaries, whereas in SSP5, the non-fossil share of PE decreases due to a societal preference for fossil fuel development. These baseline assumptions have a strong impact on the least-cost mitigation pathways associated with each SSP (Riahi, et al. 2016).

Perhaps surprisingly, PE from non-biomass renewables and BECCS are virtually equivalent in the SSP1 and SSP5 markers (i.e., P2 and P4) until 2030 (Figure 18a); however, by 2050, non-biomass renewable PE in P4 is nearly double that of P2 and BECCS PE in P4 is nearly six times that of P2 (Figure 18b and 18c). Another key difference between these scenarios is change in total final energy, which increases by around 40% in P4 and decreases by around 10% in P2 between 2010 and 2050 (Figure 18d). By comparison, PE from non-biomass renewables in P3 grows at a higher sustained rate between 2010 and 2050 than in P2 or P4; but similarly to P4, P3 still relies on substantially higher rates of CDR through BECCS and afforestation/reforestation than P2 to compensate for greater energy-related emissions between 2020 and 2050 due to its smaller reduction in total primary and final energy. The reliance of P3 and P4 on CDR also leads to higher peak warming values of around 1.6C and 1.8C, respectively, whereas P2 limits peak warming to around 1.5C. These results collectively suggest that high rates of RE deployment do

not reduce reliance on CDR unless overall energy consumption is reduced as well, resulting in steep, near-term energy-related emissions reductions.

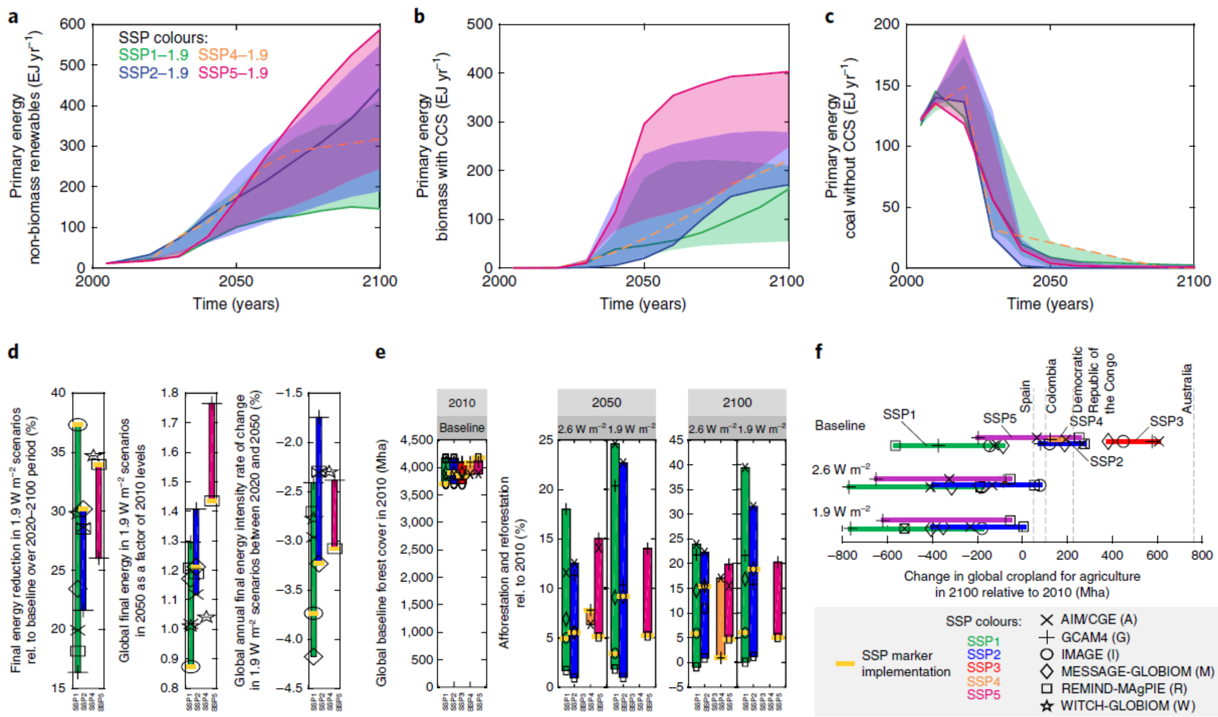

Figure 18: ***Comparison of SSP-1.9 decarbonization characteristics, including all six assessed models (i.e., not only the representative archetypes associated with each). Archetype scenarios (also called marker scenarios) for each SSP (SSP1: P2, SSP2: P3, SSP5: P4) are shown by solid lines (a-c) or yellow shading (d-e). a****, Primary energy from non-biomass renewables (wind, solar, hydro and geothermal energy).* ***b****, Primary energy from biomass with CCS (BECCS).* ***c****, Primary energy from coal without CCS. Shaded areas in a–c show the range per SSP, solid lines the marker scenarios for each SSP and dashed lines single scenarios that are not markers.* ***d****, Three illustrations of global final energy demand in 1.9 W m−2 scenarios showing, from left to right, the average reduction from baseline over the 2020–2100 period, the change in 2050 compared to 2010 levels, and the annual rate of final energy intensity change.* ***e****, Global forest cover, and change relative to 2010 due to afforestation and reforestation in 2.6 and 1.9 W m−2 scenarios.* ***f****, Change in global cropland for agriculture in 2100 relative to 2010 in 'Baseline' scenarios in the absence of climate change mitigation, as well as in 2.6 and 1.9 W m−2 scenarios (Rogelj and et al., Scenarios towards limiting global mean temperature increase below 1.5°C 2018).*

Between Scylla and Charbydis (Strefler, et al. 2018)

Strefler et al. (2018) explicitly test the impact of CDR availability on both short-term ambition (2020-2030) and transitional challenges (2030-2050) associated with limiting warming to 1.5C or 2C. In their experiment, different levels of short-term policy are implemented to reduce energy and industrial-process related CO2 emissions between 2020 and 2030, and after 2030, CDR becomes available; however, the maximal amount of CDR is also varied between 0-20 GT CO2/yr across experimental runs. Because near-term ambition and CDR availability are treated as independent variables, while 2030-2050 emissions reductions are examined as a dependent variable, the authors can identify the most "cost-effective" pairing of near-term reductions (2020-2030) and transitional reductions (2030-2050) for any upper limit imposed on CDR availability

after 2030 (Figure 19). Two of the scenarios produced by their experiment are included in the SBTi 1.5C envelope.

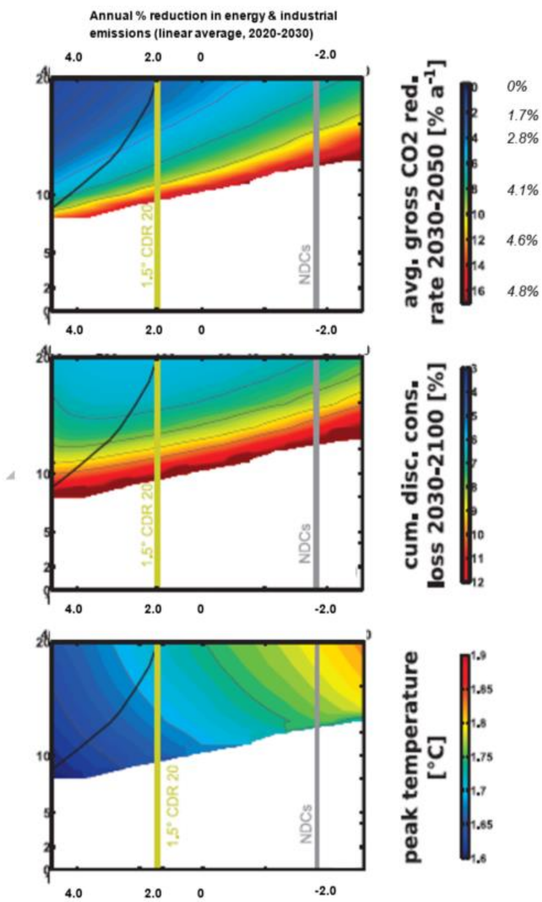

*Figure 19: Top: Average **gross** CO2 emission reduction rate 2030-2050 (**CAGR,** shaded contour) as a function of CDR availability in GT CDR/year (y-axis) and 2020-2030 linear average emissions reduction rate (x-axis). Italic numbers at the right of color scale indicate the equivalent **linear average reduction rate** 2030-2050. The black line shows the most cost-effective scenarios. Grey bar indicates the reductions 2020-2030 resulting from NDCs and yellow bar indicates the reductions from the cost-effective scenario allowing 20 GT CDR/year. Middle: cumulative discounted consumption losses (cumulated between 2030–2100 using a discount rate of 5% per year), indicator for total economic costs. Bottom: peak temperature, indicator for climate risks.*

Strefler et al. conclude that as CDR availability is reduced, both near-term and long-term ambition must dramatically increase; and that it is not possible to conserve the 1.5C CO2 budget without a maximal availability of at least 7 GT CO2/year of CDR under SSP2-like socioeconomic assumptions. They also conclude that when CDR is considered as an available option in the REMIND model, it will always result in lower near-term and long-term economic costs; however, they specify that economic costs calculated by the model do not include climate damages or mitigation co-benefits and do not reflect different degrees of climate risk – an important feature that is shared by virtually all IAMs. Accordingly, they also examine peak temperature as a proxy for climate risks and conclude that although CDR lowers economic costs as calculated by the

model, it also increases climate risks and impact costs not calculated by the model and increases technical and sustainability risks associated with mitigation.

Ratcheting ambition (Holz, et al. 2018)

Holz et al. (2018) examine the relationship between CDR deployment and near-term CO2 emissions reductions, applying an interactive scenario-building approach using the C-ROADS climate model and the En-ROADS policy model. Unlike most IAMs, C-ROADS does not generate pathways based on least-cost optimization; instead, users specify future emissions of different GHGs for each country or region of the world. Subsequently, En-ROADS may be used to generate policy and economic pathways that are consistent with GHG emissions pathways in each C-ROADS scenario. In their experiment, Holz et al. first develop a reference scenario that is consistent with existing NDCs and then develop 1.5C-aligned mitigation scenarios by iteratively increasing the ambition of current NDCs and shifting their date of completion to 2025, as well as modifying post-2025 reduction rates until warming in 2100 is limited to 1.5C. Each mitigation scenario assumes one of three different levels of CDR availability – full availability of CDR options, limited CDR availability based on Dooley and Kartha (2017), and no CDR availability – with and without overshoot.

None of Holz et al.'s scenarios were included in the SBTi or CA 1.5C envelopes, in part due to the limited set of variables reported in the SR15 database; however, two of them (no CDR and no CDR/no overshoot) appear in the bottom left quadrant of the EI Index chart (Figure 11)[11] and two more (limCDR and limCDR/no overshoot) appear in the top right quadrant. Out of these four scenarios, only the limCDR scenario could be successfully modeled by the En-ROADS policy and economic model without changing population or GDP growth projections. Their conclusion is consistent with that of van Vuuren, et al. (2018), whose experiment probes the potential of social transformations to contribute to limiting warming to 1.5C without CDR using the IMAGE model, but contradicted by Grubler, et al. (2018), whose experiment suggests that accelerating changes in the quality and type of energy services may enable a downsizing of the energy system that limits warming to 1.5C without CDR, despite SSP2-aligned population and GDP growth rates, using the MESSAGE model.

[11] They are not shown on the P Index quadrant chart (Figure 17) because power sector emissions are not included in the SR15 database for C-ROADS scenarios

8. Recommendations

Appropriate scenario selection

While the SBTi 1.5C set and the CA 1.5C set are in many ways fit for their respective purposes (determining global emissions pathways and coal phase-out rates, respectively), neither option specifically addresses the SDF requirement of demonstrating that sector and subsector pathways are allocated appropriately and that the global emissions budget is reasonably shared among other not covered sectors. Consequentially, some scenarios included in both sets rely on a 300% reduction in AFOLU CO2 emissions between 2020 and 2025 (Box 2) – a scale of transformation that top-down and bottom-estimates of 1.5C land sector pathways do not envision until around 2050 (Roe, et al. 2019).[12] To avoid scenarios that do not reasonably share the global emissions budget among sectors not covered, it is recommended that the SBTi incorporates EI Index and P Index into its scenario selection approach for sector pathways.

It is also critical for the SBTi to adopt a position on CDR that informs its scenario selection approach. Although the emissions budget filter of the SBTi 1.5C envelope eliminates some scenarios that rely on very negative net GHG emissions in the second half of the century to rectify overshoot, it does not identify scenarios that rely on high, sustained rates of gross CDR before or after achieving net zero emissions. High reliance on gross CDR is associated with some less ambitious PE sector emissions pathways due to the potential of AR-related CDR to compensate for higher, residual PE sector emissions, and a much greater spread in PE product emissions pathways due to the potential of BECCS to enable higher, residual fossil PE emissions. All of the CDR approaches included in IAMs face enormous challenges to implementation and governance, which would need to bear on the long-term storage/permanence of sequestered carbon and associated liability for leakage, as well as uncertain property rights and potential land conflicts (Lin 2019). While the importance of CDR should not be discounted in principle and practice, the near-term ambition of methods endorsed by the SBTi should not be affected by scenarios where high rates of assumed CDR prolong the emitting lifespan of fossil fuel assets. Thus, it is recommended that the SBTi incorporates cumulative CDR into its scenario selection approach for sector pathways, and that the determination of an allowable range of CDR should be specified not based on its statistical representation among scenarios, but rather based on considerations beyond the scope of what is covered by IAMs.[13]

Science-based approaches to CDR

The SBTi is founded on the principle that if all companies in the global economy were to set and achieve SBTs, emissions would be reduced in line with what is needed to limit warming to 1.5C

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[12] By comparison, IEA's 2DS and B2DS assume that AFOLU CO2 emissions reach zero around 2045

[13] Researchers have noted that while it is virtually impossible to limit warming to 1.5C without some CDR, the very high rates of CDR depicted by scenarios in the SR15 Scenario Database reflect the influence of experimental design choices, like solving only for a long-term temperature goal and not incorporating the climate impact costs associated with temperature overshoot, rather than signaling robust conclusions (Rogelj, Huppmann, et al. 2019) (Strefler, et al. 2018) (Lomax and Workman 2015). In fact, Rogelj et al. demonstrate

or well-below 2C. For example, if all companies set absolute contraction targets, company-related emissions would be reduced by about 50% between 2018 and 2030 consistent with global reduction rates (Science Based Targets initiative 2019). Additionally, when IEA's 2DS or B2DS scenarios are used with the SDA, the sum of all underlying sector budgets is equal to a clearly defined energy and industrial processes CO2 budget, which excludes the projected contributions of non-CO2 GHGs and AFOLU emissions based on top-down and bottom-up estimates assuming significant effort. In other words, emissions not covered by the method are static estimates with limited potential to compensate for higher residual emissions in the global economy.

Additionally, the SDA approach is designed to preserve underlying sector budgets, which are equal in sum to a separately determined energy and industrial processes CO2 budget when IEA's 2DS or B2DS scenarios are used. The budgets underlying 2DS and B2DS exclude the projected contributions of non-CO2 GHGs and AFOLU emissions based on an assessment of AR5 scenarios and bottom-up estimates assuming significant effort; in other words, emissions excluded from the scope of the target-setting method are static estimates with very limited potential to compensate for higher residual emissions in the global economy (International Energy Agency 2017)[14].

In many IPCC scenarios, however, CDR – often deployed outside the scope of existing economic sectors – is dynamically balanced with emissions that originate within established sectors of the global economy. For a method to adequately represent the characteristics of a scenario that relies heavily on CDR, there are two options:

1. Removals are included as pathways for new sectors of the economy (e.g., bioenergy SBT pathway, direct air capture SBT pathway);
2. Removals are allocated to existing sectors (e.g., oil & gas) by the target-setting method.

The first option is not viable because nascent CDR sectors would have no incentive or responsibility to sequester carbon without compensation. They exist effectively to "offset" the residual emissions of others. Moreover, their reductions would be double counted if target-setting companies in existing sectors relied on the CDR sector to comply with their own sectors' pathways, while the CDR sector accounted those same negative emissions toward its own SBT pathway. To be consistent with the global emissions pathway and budget, target-setting companies in existing sectors would need to achieve their targets as *gross* reductions and the CDR sector would need to achieve its pathway additionally.

The second option is more consistent with ensuring that global emissions would be reduced in line with what is needed to limit warming, but in many cases, it would be challenging to determine how to allocate removals among SDA sectors, subsectors, and target-setting companies. Allocating removals would be particularly important for scenarios in either right-hand quadrant of

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[14] The IEA's 2DS and B2DS scenarios both assume AFOLU-related emissions contribute a net total of -30 GtCO2 emissions between 2010-2100

the EI-CDR chart (Figure 11). For scenarios in either bottom quadrant of the EI-CDR chart, however, removals could be adequately covered simply by using sector-wide pathways rather than subsector, PE product pathways because BECCS-related CDR is already reflected by the PE sector's net emissions pathway.[15]

Alternatively, the SBTi could adopt scenario(s) that rely on minimal CDR, which would avoid the challenges associated with allocating removals between PE subsectors, and define separate criteria for how companies are able to deploy CDR measures to achieve their target in practice. For example, the Oil & Gas sector could be assigned a net emissions pathway based on each product's respective emissions budget in P1; and separate criteria could specify the maximum amount of CDR that companies are allowed to use to achieve their net reduction target.

[15] Scenarios in the upper left quadrant should never be used because allocating gross land-use related reductions is not feasible and the scenarios may lack in credibility. Although neither scenario in the upper left quadrant of Figure 11 relies on high rates of sustained CDR later in the century, both assume 300% reductions in AFOLU emissions between 2020 and 2025, which substantially enlarges the energy and industrial processes emissions budget

9. Conclusion

This whitepaper represents a thorough, purpose-driven assessment of 1.5C-aligned energy system transformations based on mitigation scenarios in the SR15 scenario database. First, five different approaches to identifying Paris-aligned scenarios are compared and existing principles underlying the SBTi's approach to sector development are reviewed. Next, characteristics of the energy system transition are examined in overview. The role of CDR within the energy system, as well as in the land-use sector, is discussed. Key indicators for the primary energy sector and the power sector are utilized to shed light on important differences between scenarios, which should be carefully considered by standard-setters in the selection of scenarios and interpretation of pathways. The preceding results are contextualized with an assessment of existing scientific literature with an emphasis on experiments that examine the relationship between short and medium-term ambition and deployment of CDR. Lastly, a set of recommendations is provided that may advance and justify the SBTi's approach to selecting scenarios to underly both the Oil & Gas and Power sector method development projects.

This whitepaper should be understood and utilized as an objective review of the relevant science, framed by existing SBTi principles and parallel work that has been conducted by the climate action community. As such, it does not prescribe any one approach to how scenarios should be interpreted; rather, it recommends specific guidelines and constraints that should be followed to ensure that scenarios are appropriately and transparently interpreted by standard-setters. Future work produced by CDP and the SBTi will directly respond to recommendations laid out by this whitepaper. The SBTi is expected to issue technical annexes that may draw from the EI Index-CDR and P Index-CDR quadrant charts to aid in scenario selection, pathway interpretation, and treatment of CDR. In the near future, the SBTi will utilize the findings of this whitepaper to aid in the selection of a 1.5C-aligned power sector pathway; while in the longer-term, its findings may be reflected by Oil & Gas sector methodologies.

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Version history

Version	Date	Description
Oil & Gas Whitepaper V1.4	11/7/2019	- Some sections still to be written; - First draft shared with CDP Oil & Gas TWG and SBTi TWG;
Energy system whitepaper V2.0	12/16/2019	- Minor adjustments to the CA 1.5C scenario set and all figures; - Expanded scope of paper to explicitly include power sector transformations, in addition to PE sector transformations, and add section "Key indicators of the power sector." Renamed paper accordingly; - All sections except Supplementary Text 1 complete; - Added a "Version history" section; - Shared with CDP Oil & Gas project team.
Energy system whitepaper V2.1	1/27/2020	- Minor revisions to "Introduction", "Discussion", "Recommendation", and "Conclusions"; - "Supplementary Text 1" and associated figures complete; - Shared with a chosen set of reviewers for comment
Energy system whitepaper V2.2	4/1/2020	- Minor edits to CDR text in Section 5 based on reviewer feedback

Supplementary Materials

Supplementary Text 1 – Well-below 2C assessment

In this section, the SBTi well-below 2C (WB-2C) set is compared to the unfiltered collection of scenarios in SR15 that hold warming to under 2C during the entire 21st century (>66% probability) and the IEA ETP 2017 Below 2C Scenario (B2DS). B2DS is aligned with the SBTi WB-2C set based on a comparison of energy and industrial CO2 emissions reduction rates between 2020 and 2040 and currently underlies the SBTi's WB-2C-aligned sectoral methods (Science Based Targets initiative 2019). Forthcoming assessments may also examine pathways from newer IEA scenarios such as the Sustainable Development Scenario (SDS) (International Energy Agency 2019).

A key difference between IEA scenarios and the SR15 scenarios examined in this report is that IEA scenarios are limited to energy and industrial process-related CO2 emissions, whereas scenarios in the SR15 database must also include AFOLU-related emissions and non-CO2 GHG emissions. IEA scenarios and others not included in the SR15 database tend to exclude AFOLU-related emissions and non-CO2 GHG emissions from the scope of modelling because those emissions are characterized by the greatest amount of uncertainty; however, they are also needed to estimate the probabilistic amount of global warming associated with any scenario, making it hard to directly compare IEA scenarios with those included in the SR15 database.

One of the recommendations laid out in Section 8 of this report is that the SBTi should limit its scenario selection to those with AFOLU-related emissions pathways consistent with bottom-up estimates of what the land sector can sustainably achieve. That approach would most likely align with the assumptions underlying most IEA scenarios. For example, the B2DS scenario was designed with an energy and industrial process-related CO2 emissions budget intended to limit warming to under 2C (>66% probability), assuming that AFOLU-related emissions reach zero around 2045, which is consistent with some recent estimates of ambitious land-use pathways (Roe, et al. 2019). The SDS provides less detail on its AFOLU-related assumptions, but also aims to hold temperature rise to below 1.8C with a 66% probability without reliance on global net-negative CO2 emissions, which are generally dominated by BECCS and/or AR.

Between 2020 and 2060, B2DS depicts lower energy-related emissions than the interquartile range of scenarios in the SBTi WB-2C envelope (Supplementary Figure 4); and some B2DS pathways are within the range of ambition of scenarios in the SBTi 1.5 and CA 1.5C sets. This is likely due in part to the historicity of B2DS, which depicts emissions peaking around 2015, as well as greater dependence on CDR in many SR15 scenarios relative to B2DS. Forthcoming assessments will compare more recent IEA scenarios to those present elsewhere in the scientific literature.

Supplementary Text 2 – Description of CA's filter methodology

Climate Analytics applied a three-step filter to select scenarios for inclusion in *Global and regional coal phase-out requirements of the Paris Agreement*. Literature estimates of CDR potentials for

2050, which establish a range from 0.5 - 5 GtCO2/year (for BECCS), and 0.5 - 3.6 GtCO2/year AFOLU in 2050, are utilized in steps 2 and 3 (Fuss 2018):

1. Keep pathways which are classified as "1.5°C low overshoot" or "Below 1.5°C" in the SR15 database;
2. Filter out pathways where the average value (for 2040, 2050 and 2060) of "Carbon Sequestration|CCS|Biomass" exceeds 5 GtCO2/yr. The choice of this average value for the filter is to account for pathways which show an anomalous increase beyond 5 GtCO2/year in 2060;
3. We filter out pathways where the average value (for 2040, 2050 and 2060) of "Emissions|CO2|AFOLU") is lower than -3.6 GtCO2/yr.

Supplementary Text 3 – KI calculation methodologies

The level of precision of analyses in this whitepaper is subject to both practical and theoretical constraints. At a practical level, not all of the KIs are directly "mappable" to variables in the SR15 database, and it would be inefficient to acquire separate data from each modeling team if KIs can be suitably *estimated* based on variables in the SR15 database. Additionally, scenarios in the SR15 database have different subsets of variables reported (out of 540 variables that were requested by IIASA, 29 were specified as mandatory and 173 were specified as high priority), which means that certain calculations are possible for some scenarios and not others. On a theoretical level, the IAMs underlying scenarios in the SR15 database are characterized by a wide range of resolutions and representations of the energy system. Estimations that are applicable to a wide range of models are preferred to those that are only relevant to a few.

Calculation methodologies used in the report are documented below. Quoted variables are those included in the SR15 database, which are defined in the IPCC SR15 data reporting template, unquoted variables are those calculated elsewhere for the whitepaper, and italicized variables are assumed constants. Some KIs include more than one equation, indicating a tiered estimation approach (e.g., if variable A is available use equation 1, and if not use equation 2).

KI calculation methodologies

KI	Equation	Comments
PE consumption	"Primary Energy"	
PE-related emissions	1. "Emissions|CO2|Energy|Demand" + "Emissions|CO2|Energy|Supply" 2. "Emissions|CO2|Energy and Industrial Processes"	Equation 1 is applied to around 90% of scenarios, but some scenarios do not report energy-related emissions separately from energy and industrial process-related emissions (which may also include direct emissions from processing feedstocks). In some cases, the model itself may not differentiate between energy and industrial process-related emissions.

PE emissions intensity	PE-related emissions/PE consumption	
AFOLU-related CDR	If "Emissions|CO2|AFOLU" < 0: -"Emissions|CO2|AFOLU" Else if "Emissions|CO2|AFOLU" > 0: 0	
CDR	"Carbon Sequestration|CCS|Biomass" + AFOLU-related CDR + "Carbon Sequestration|Direct Air Capture" + "Carbon Sequestration|Enhanced Weathering" (for all reported)	Only around 6% of scenarios reported each "Carbon Sequestration|Direct Air Capture" and "Carbon Sequestration|Enhanced Weathering"
EI Index	"Emissions|CO2|Energy and Industrial Processes"/"Emissions|Kyoto Gases"	
Gas, Oil, Coal, Biomass activity	"Primary Energy|{PE product}"	
Gas, Oil, Coal emissions	"Primary Energy|{PE Product}|w/o CCS" * *{PE product LHV to HHV conversion factor}* * *{PE product CO2 emissions factor}*	Assumes that fossil PE product emissions are proportional to non-CCS PE product consumption
Biomass emissions	-"Primary Energy|Biomass|w/ CCS" * *Biomass LHV to HHV conversion factor* * *Biomass CO2 emissions factor*	Assumes that negative biomass emissions are proportional to CCS-equipped Biomass PE consumption
Gas, Oil, Coal, Biomass emissions intensity	{PE Product emissions}/{PE product activity}	
Electricity production	"Secondary Energy|Electricity"	
Electricity-related emissions	"Emissions|CO2|Energy|Supply|Electricity"	
Electricity emissions intensity	Electricity-related emissions/Electricity production	
P Index	"Emissions|CO2|Energy|Supply|Electricity"/ "Emissions|Kyoto Gases"	

Supplementary Figure 1 (Figure 20)

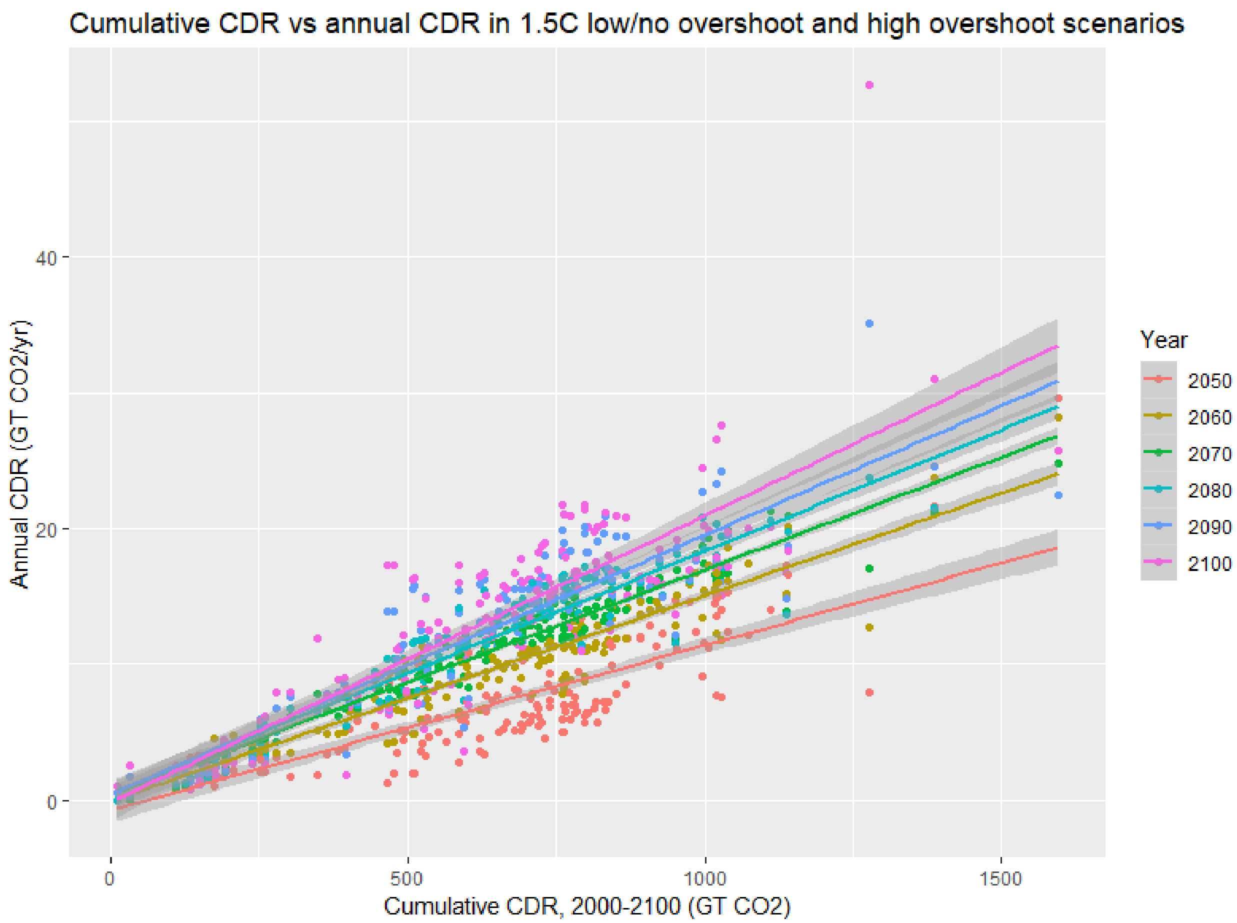

Figure 20: Cumulative CDR vs annual CDR in 1.5C low/no overshoot and high overshoot scenarios, plotted for annual CDR measured each decade between 2050 and 2100. Scenarios with large amounts of cumulative CDR between 2000-2100 require increasing rates of annual CDR between 2050-2100. Cumulative CDR is most strongly correlated to annual CDR in 2070 with an R^2 *value of 0.95.*

Supplementary Figure 2 (Figure 21)

Figure 21: EI Index relative to 1.5C low/no-overshoot set median (average of 2030, 2040 and 2050) vs CDR with model-scenario labels (top). P Index relative to 1.5C low/no-overshoot set median (average of 2030, 2040, and 2050) vs CDR with model-scenario labels (bottom). Chart is divided into quadrants where the vertical line demarcates scenarios with over/under 7.2 GT CO2/year and the horizontal line demarcates scenarios with EI Indices over/under the 1.5C low/no-overshoot median in the given year. Scenarios with >15 GT CDR/yr are not shown.

Supplementary Figure 3 (Figure 22)

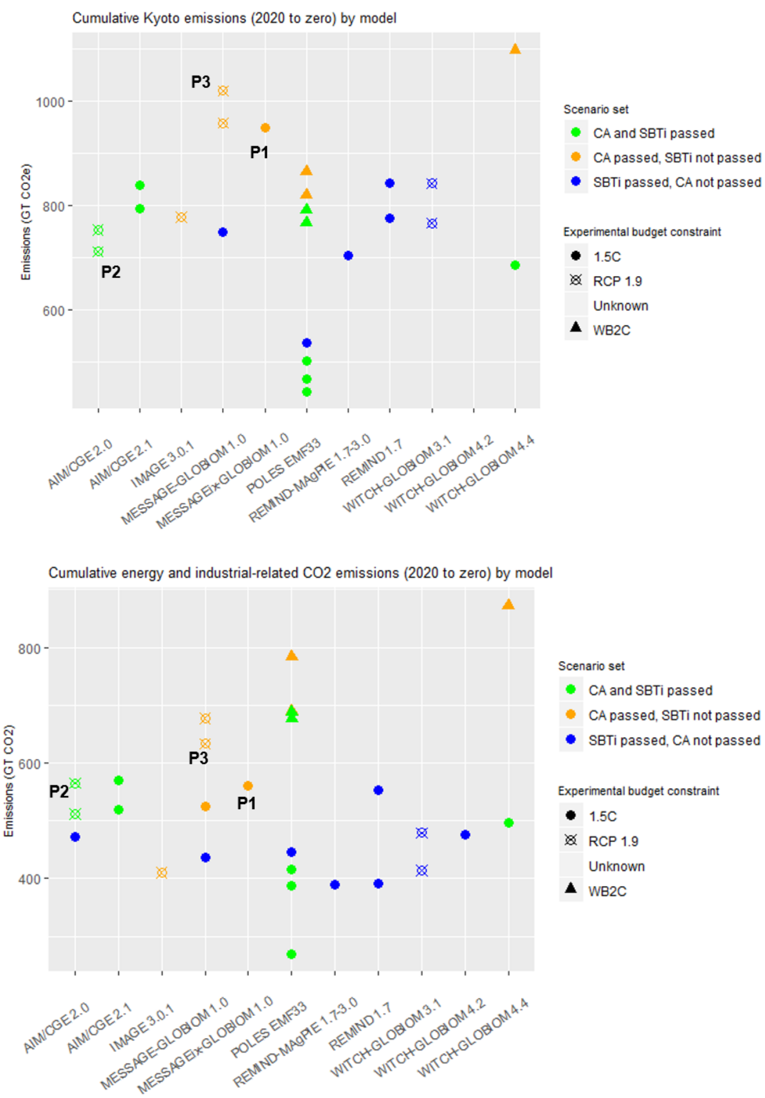

Figure 22: Cumulative Kyoto gas emissions (top) and energy and industrial process-related CO2 emissions (bottom) between 2020 and year of zero emissions across all scenarios included in the CA 1.5C set or SBTi 1.5C. Model is shown on the x-axis and archetype scenarios are labeled. P1 and P2 correspond to the CTI definition of Paris-aligned scenarios. The IEA SDS scenario is not shown, as emissions data is only available for 2018-2040.

Supplementary Figure 4 (Figure 23)

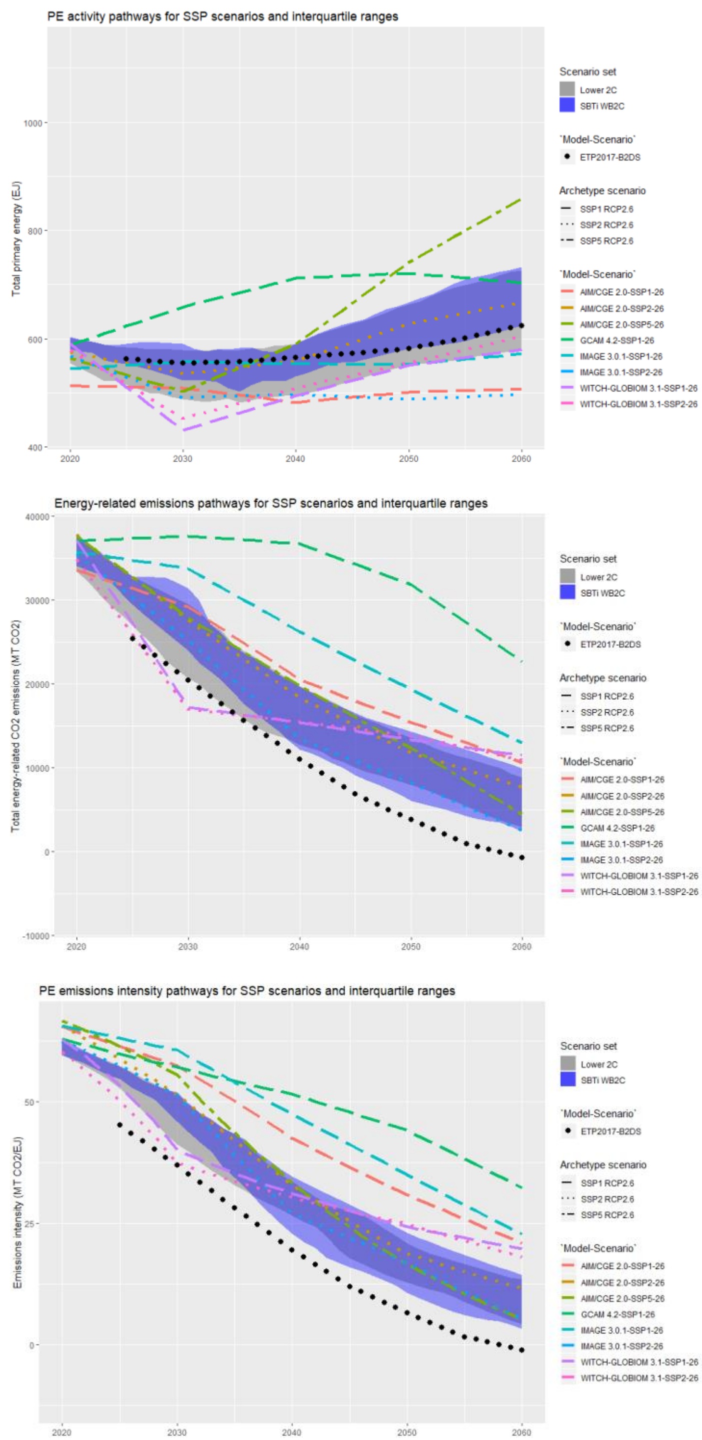

Figure 23: PE consumption (top), PE-related emissions (middle), and PE emissions intensity (bottom) across the SBTi WB-2C envelope (blue), Lower 2C scenario envelope (grey), Lower 2C RCP2.6 SSP scenarios (colored lines), and IEA ETP 2017 B2DS (black dotted line).

Supplementary Table 1 – Primary Energy KIs for the SBTi 1.5C envelope

Key indicator	Median and interquartile range	Mean	Standard deviation
Total			
PE emissions reduction	70% (65%-74%)	71%	8.1%
PE activity reduction	25% (18%-32%)	26%	11%
PE intensity reduction	59% (54%-66%)	61%	9.6%
Oil			
Oil-related emissions reduction	50% (47%-56%)	49%	13%
Oil-related activity reduction	49% (43%-56%)	48%	14%
Oil-related intensity reduction	0% (0%-2.6%)	1.6%	4.3%
Gas			
Gas-related emissions reduction	59% (54%-67%)	60%	19%
Gas-related activity reduction	51% (43%-64%)	49%	31%
Gas-related intensity reduction	17% (14%-22%)	20%	12%
Coal			
Coal-related emissions reduction	87% (82%-93%)	87%	7.1%
Coal-related activity reduction	82% (74%-86%)	81%	10%
Coal-related intensity reduction	21% (6.1%-32%)	26%	26%
Biomass			
Biomass-related emissions in 2035	-610 MT CO2 (-1600 to -290 MT CO2)	-1000 MT CO2	930 MT CO2
Biomass PE consumption in 2035	110 MWh (87 MWh to 140 MWh)	100 MWh	27 MWh
Biomass intensity in 2035	-5.4 MT CO2/MWh (-15 MT CO2/MWh to -3.8 MT CO2/MWh)	-11.4 MT CO2/MWh	12 MT CO2/MWh

Supplementary Table 2 – Primary Energy KIs for the CA 1.5C envelope

Key indicator	Median and interquartile range	Mean	Standard deviation
Total			
PE emissions reduction	64% (52%-70%)	62%	13%
PE activity reduction	21% (18%-30%)	24%	12%
PE intensity reduction	52% (42%-58%)	51%	12%
Oil			
Oil-related emissions reduction	49% (36%-54%)	46%	16%
Oil-related activity reduction	47% (34%-54%)	45%	16%
Oil-related intensity reduction	0% (0%-2.3%)	1.4%	3.0%
Gas			
Gas-related emissions reduction	50% (26%-57%)	42%	25%
Gas-related activity reduction	42% (9.1%-51%)	30%	34%
Gas-related intensity reduction	16% (12%-21%)	16%	11%
Coal			
Coal-related emissions reduction	82% (78%-88%)	82%	7.4%
Coal-related activity reduction	77% (69%-84%)	76%	9.7%
Coal-related intensity reduction	18% (5.9%-29%)	22%	22%
Biomass			
Biomass-related emissions in 2035	-450 MT CO2 (-780 MT CO2 to -210 MT CO2)	-570 MT CO2	590 MT CO2
Biomass PE consumption in 2035	87 MWh (67 MWh to 110 MWh)	29 MWh	28 MWh
Biomass intensity in 2035	-4.4 MT CO2/MWh (-8.7 MT CO2/MWh to -2.4 MT CO2/MWh)	-7.3 MT CO2/MWh	8.5 MT CO2/MWh

Supplementary Table 3 – Primary Energy KIs for the 1.5C low/no-overshoot set

Key indicator	Median and interquartile range	Mean	Standard deviation
Total			
PE emissions reduction	62% (51%-70%)	61%	13%
PE activity reduction	18% (8.0%-24%)	17%	14%
PE intensity reduction	53% (42%-60%)	52%	12%
Oil			
Oil-related emissions reduction	43% (18%-50%)	36%	21%
Oil-related activity reduction	40% (18%-50%)	35%	20%
Oil-related intensity reduction	0% (0%-1.5%)	1.4%	3.0%
Gas			
Gas-related emissions reduction	40% (29%-56%)	39%	26%
Gas-related activity reduction	30% (1.1%-48%)	26%	33%
Gas-related intensity reduction	16% (8%-22%)	16%	11%
Coal			
Coal-related emissions reduction	82% (75%-90%)	82%	10%
Coal-related activity reduction	79% (68%-86%)	77%	12%
Coal-related intensity reduction	21% (6%-29%)	21%	22%
Biomass			
Biomass-related emissions in 2035	-630 MT CO2 (-1700 MT CO2 to -290 MT CO2)	-1400 MT CO2	1800 MT CO2
Biomass PE consumption in 2035	99 MWh (75 MWh to 120 MWh)	97 MWh	31 MWh
Biomass intensity in 2035	-5.8 MT CO2/MWh (-21 MT CO2/MWh to -3.0 MT CO2/MWh)	-14 MT CO2/MWh	14 MT CO2/MWh

Supplementary Table 4 – EI Index comparison across scenarios

Scenario set or archetype	2020	2035	2050
EI Index			
SBTi 1.5C	0.68 (0.65-0.75)	0.73 (0.60-0.92)	0.54 (0.3-0.67)
CA 1.5C	0.69 (0.68-0.75)	0.76 (0.65-0.95)	0.61 (0.45-0.83)
1.5C low/no overshoot	0.68 (0.67-0.71)	0.75 (0.6-0.86)	0.5 (0.21-0.85)
P1	0.67	0.62	0.47
P2	0.67	0.81	1.0
P3	0.68	0.66	0.51

Supplementary Table 5 – Power sector KIs

Key indicator	Median and interquartile range	Mean	Standard deviation
SBTi 1.5C			
Power-related emissions reduction	87% (78%-98%)	89%	13%
Power-related activity increase	50% (14%-70%)	46%	34%
Power-related intensity reduction	92% (86%-99%)	92%	9%
CA 1.5C			
Power-related emissions reduction	78% (71%-85%)	79%	12%
Power-related activity increase	18% (7%-45%)	32%	34%
Power-related intensity reduction	88% (78%-89%)	84%	10%
1.5C low/no overshoot			
Power-related emissions reduction	83% (70%-92%)	82%	18%
Power-related activity increase	38% (15%-69%)	42%	32%
Power-related intensity reduction	88% (78%-95%)	87%	14%