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Institutional "Paris Agreement Compatible" Mitigation Scenarios Evaluated Against the Paris Agreement 1.5°C Goal

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Abstract

Since its adoption in 2015, governments, international agencies and private entities have increasingly recognized the implications of the Paris Agreement's 1.5°C long-term temperature goal (LTTG) for greenhouse gas emissions reduction planning in both the near- and long-term. Governments have submitted or are preparing updates of their Nationally Determined Contributions (NDCs) and are encouraged to submit long term low greenhouse gas development plans (Article 4 of the Agreement[1]), aimed at aligning short- and long-term strategies. The foundations on which country targets are based are guided, directly or indirectly, by a variety of sources of information judged to be authoritative, including scientific research institutes[2], international agencies, or private companies. Importantly, such authoritative sources also affect planning and decision making by investors[3] who aim to anticipate climate policies, and their decisions in turn can drive or hold back setting ambitious emissions-reduction targets.

Assessing if a given emissions mitigation pathway (here, we use the term "scenario" synonymously) adheres to the Paris Agreement requires some historical context of the climate negotiation process. The Cancun Agreement had previously established a goal of limiting global temperature to "below 2°C"[4], which was interpreted by the scientific community as a 66% probability (or 'likely' chance) of maintaining this limit[5]. Article 2.1.a of the Paris Agreement strengthens this target to "holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C", while Article 4.1 requires parties to "achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases"[1]. The strengthened temperature goal therefore requires a substantially higher margin and likelihood of holding warming below 2°C, for example the "very likely" level of 90% probability of not exceeding 2°C, as well as achieving net-zero emissions in this century[6]. Further, pathways highlighted by the Intergovernmental Panel on Climate Change (IPCC) in the Summary for Policymakers (SPM) of the Special Report on Global Warming of 1.5°C (SR1.5) are "as likely as not" to limit warming to 1.5°C by the end of the century (i.e., with 50% probability)[7]. Scenarios that achieve these three climatic outcomes can be considered Paris Agreement compatible[8].

A large number of emission mitigation pathways generated by Integrated Assessment Models (IAMs) have been assessed and categorized with respect to their climate outcomes[9]. Most IAMs represent different greenhouse gases and aerosol precursors over a long-term horizon (2100), a necessary characteristic for assessing the consistency with the Paris Agreement LTTG. The SR1.5 database also included a small selection of non-IAM pathways (including two scenarios from the International Energy Agency, and one from Shell). Whereas the climate outcomes of the IAM pathways were assessed by the SR1.5 author team, the temperature statements of the non-IAM pathways were self-assessed.

IEA and Shell are among a number of influential organizations publishing scenarios in the grey literature that claim consistency with the Paris Agreement LTTG. However, this has not been verified by a peer-reviewed, transparent temperature assessment of these "institutional" and other non-IAM scenarios on an equal footing with IAM scenarios. We present the challenges to such an assessment and implement a framework to analyze the climate outcomes of these scenarios. We further assess key underlying energy system features that drive emissions pathways, thus providing an evaluation of the structural dynamics that lead a given scenario to satisfy (or not) the Paris Agreement LTTG.

Challenges to assess climate impact of institutional scenarios

Skea *et al*. propose a categorization of energy system scenarios in terms of being *outlooks*, *exploratory*, or *normative*[10]. *Normative scenarios* are explicitly associated with the achievement of a desired end state (in this case, a temperature goal) and have primarily been the subject of investigation by the Integrated Assessment Modelling community. Here, we define "institutional scenarios" as normative scenarios modelled by organizations that have historically been most associated with either *outlook* or *exploratory* scenarios, and we assess scenarios from institutions including Shell[11], BP[12], the IEA[13,14], and Equinor[15] – these scenarios explicitly claim consistency with the Paris Agreement LTTG (*Table 1*).

We identify three challenges to understanding the stated climate outcome of published institutional emission pathways. These include the time horizon of the scenarios, the limited representation of greenhouse gases, aerosol emissions, and inconsistent, opaque assessments of climate outcomes. Most scenarios (except the "Sky 1.5" scenario from Shell) do not extend beyond mid-century. "Outlook" scenarios were intended to provide policy makers and other stakeholders an expert view of likely developments in the energy sector over the time scale of one or two decades. Due to large uncertainties, alternative scenarios are proposed that try to cover a range of potential technological or socioeconomic developments. Uncertainties increase significantly over longer time horizons, however, the temporal scope of the Paris Agreement necessitates both near-term (*i.e.*, peak warming) and long-term (i.e., end-of-century warming) evaluation to assess compatibility with the LTTG.

The second key challenge is that most institutional scenarios focus on CO_2 emissions from the energy sector (and sometimes include industrial process emissions). To evaluate the temperature outcome, a representation of all greenhouse gases and aerosol precursor emissions is needed, including non-energy CO_2, emissions from land use, land use change and forestry, and non-CO_2 emissions (from methane, for instance). Some institutional scenarios, such as the IEA NZE scenario include some discussion of these emissions but do not report detailed data in their publicly available scenario data, preventing a thorough comparison. The Sky 1.5 scenario from Shell is the only scenario we assess here that represents a detailed greenhouse gas emission pathway or presents any data on aerosol precursor emissions (although the only aerosol precursor it includes is SO_2).

The final challenge identified here is transparency in the quantification of the climate impact of the scenario. There are three manifestations of this problem in the scenarios we assess. First, some scenarios (including the IEA Sustainable Development Scenario, and the BP scenarios) make references to temperature outcomes that are difficult to trace back to a concrete assessment. Second, some scenarios present carbon budget constraints that vary widely for the same temperature goal; for example, the Equinor Rebalance scenario and the Shell Sky scenarios report carbon budgets larger than 700 $GtCO_2$, but only Shell claims to achieve the 1.5°C goal. Third, even where a climate model is used to assess the climate outcomes (*e.g.*, Shell Sky), the comparability with the simplified climate model parameters used in the IPCC assessments is limited.

Table 1 Institutional scenario characteristics - claims, time horizon and gas coverage

Institution (Scenario)	Scenario Claim	Scenario Endpoint	Gas Coverage
Equinor[15] ("Rebalance")	Page 33: "Rebalance is designed to be a well below 2°C scenario, and we assume cumulative emissions of 740 Gt for the 2018-50 time period to be within this target"	2050	Energy CO_2
Shell ("Sky 1.5")	Page 93: "The Joint Program analysis of the Sky 1.5 scenario implies a carbon budget that is higher than the 580 Gt number presented by the IPCC, yet still results in warming of 1.5°C in 2100, albeit with overshoot to around 1.7°C in the middle of the century. […] the implied central estimate (median) carbon budget for 1.5°C is 747 Gt CO2."	2100	Energy CO_2 Industrial Process CO_2 AFOLU CO_2 CH_4 N_2O HFCs PFCs SF_6
BP[12] ("Rapid")	Page 13: "[…] which cause carbon emissions from energy use to fall by around 70% by 2050. This fall in emissions is in line with scenarios which are consistent with limiting the rise in global temperature by 2100 to well below 2-degrees Celsius above pre-industrial levels."	2050	Energy CO_2
BP[12] ("Net Zero")	Page 13: "Global carbon emissions from energy use fall by over 95% by 2050, broadly in line with a range of scenarios which are consistent with limiting temperature rises to 1.5-degree Celsius."	2050	Energy CO_2
IEA[13] ("SDS")	Page 102: "If emissions were to remain at zero from 2070, the SDS would provide a 50% probability of limiting the temperature rise to less than 1.65°C, in line with the Paris Agreement objective of "holding the increase in global average temperature to well below 2°C". If negative emissions were to be deployed after 2070 in the SDS, the temperature rise in 2100 could be limited to 1.5°C with a 50% probability."	2040	Energy and Industrial Process CO_2
IEA[14] ("NZE")	Page 48: "In parallel with action on reducing all other sources of GHG emissions, achieving net-zero CO2 emissions from the energy sector by 2050 is consistent with around a 50% chance of limiting the long- term average global temperature rise to 1.5 °C without a temperature overshoot"	2050	Energy and Industrial Process CO_2

A framework to assess the climate impact of institutional scenarios

Given the relative opacity in the self-assessed climate impact of institutional scenarios, we propose a consistent set of steps to perform such an assessment, in a manner that allows for comparison with IAM scenarios (*Figure 1*). We briefly outline the steps here, with further details presented in *Methods.* We first check if the scenarios extend until 2100 - if not, we extend the data from the last available year until 2100 using the Constant Quantile Extension (CQE) method[16]. The CQE method extends an emission trajectory by applying the position (quantile) of the last reported data point with respect to a distribution of emissions scenarios and applying the same position to future timesteps. The CQE method has previously been applied to extend the emission levels implied by the Nationally Determined Contributions (NDCs) that are defined until 2030 [17,18]. Adding to the existing publications of the method, we study its robustness in further detail in *Supplementary Material Section 1*.

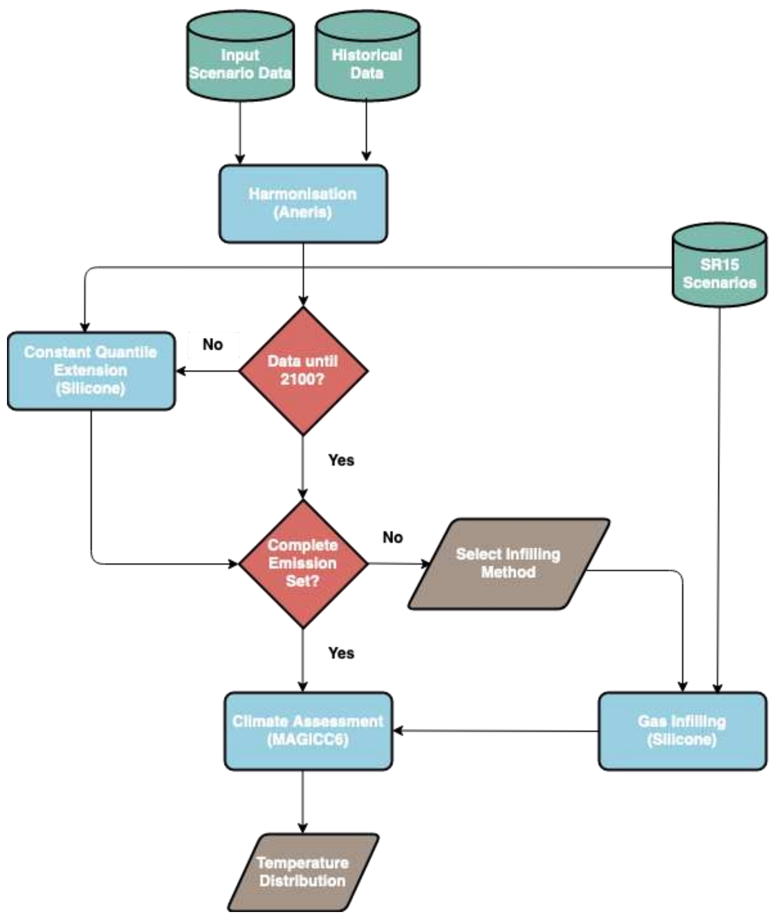

Figure 1 *Assessment framework*

We then proceed to infer missing emission species using the Quantile Rolling Windows (QRW) infilling method, a technique that has been previously applied and documented[19]. Where a scenario provides a discussion of missing emission species in the report, but does not report a timeseries in the public data, we still select this method as a default for reasons of transparency. The impact of alternative infilling methods can be found in the *Supplementary Table S2*. The resulting multi-gas emission trajectories are provided as an input to the reduced complexity coupled carbon cycle and climate model MAGICC6[20] in its probabilistic setup. The scenarios are then classified using the same algorithm as in SR1.5. Any reduced complexity climate model (e.g., FaIR[21]) which implements the *openscm* interface can be similarly applied.

Evaluating the multi-gas emission trajectories

The key variable for each scenario is CO_2 emissions from energy and industrial processes, whose relationship with other variables helps us construct a multi-gas emissions pathway (the process of deriving a multi-gas emissions pathway based on CO2 emissions alone is termed "infilling"). Comparing the values for this key variable in the SR1.5 database and the institutional scenarios provides a first order approximation of the climate implications of the institutional scenarios (*Figure 2a*). The two pathway classes in the SR1.5 that meet the warming limit of the Paris Agreement result in 2030 emission levels of 13.6 $GtCO_2$ [13.2 - 16.1 interquartile range] for the "Below 1.5C" (henceforth referred to as no overshoot pathways) category and 21 $GtCO_2$ [18.6 - 22.6 interquartile range] for the "1.5C low overshoot" category. Apart from the IEA NZE scenario (that is close to the median of the low overshoot pathways), all other institutional scenarios assessed here are either above the interquartile range of the low overshoot pathways or, in the case of Shell's Sky 1.5 scenario, outside the range of the low overshoot pathways. By 2050, the IEA NZE scenario lies below the median of the low overshoot pathways, and the Shell Sky 1.5 scenario remains above the low overshoot pathways as well as the interquartile range of the "1.5C high overshoot" (henceforth referred to as high overshoot pathways) pathways.

The reported energy and industry CO_2 emissions have implications for the infilled greenhouse gases, notably for CO_2 emissions from Agriculture, Forestry and Land Use (AFOLU), CH_4, and N_2O emissions. Methane emissions (*Figure 2c*) reach 2030 levels of 156 Mt CH_4 (129 - 248 interquartile range) for the no overshoot pathways and 236 Mt CH_4 (189 - 257 interquartile range) for the low overshoot pathways. In comparison, the Sky 1.5 scenario from Shell reaches a 2030 level of 426 Mt CH_4, which is above the interquartile range of even the high overshoot scenarios. We explore the reasons for sensitivity to infilling methods and related analytical considerations in further detail in *Supplementary Information Section 2*.

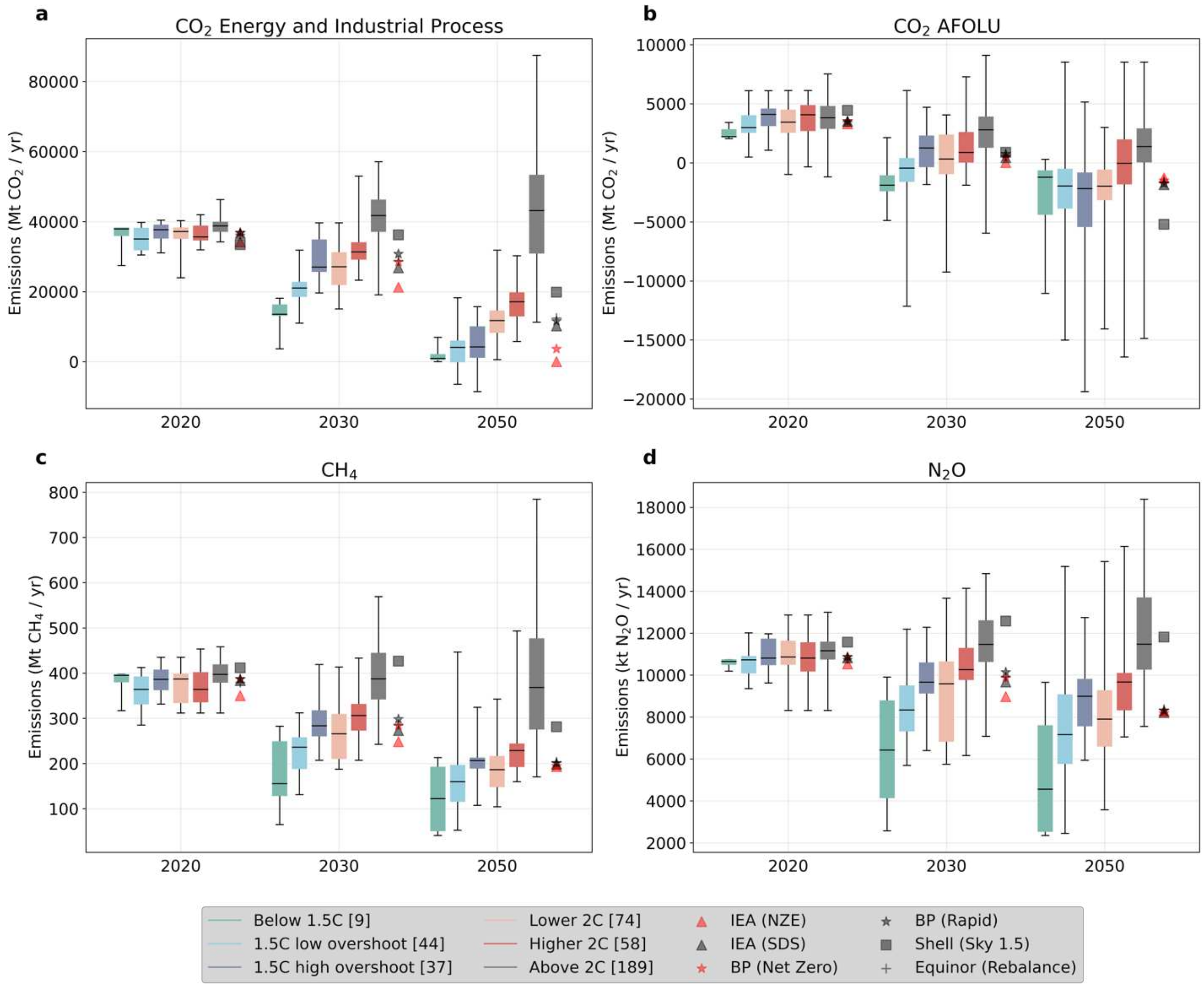

__Figure 2__ Comparing emission characteristics between the SR1.5 pathways and the institutional scenarios assessed in this study. All emissions (apart from panel a) are infilled using the QRW method, except for Shell Sky 1.5 which reports these emissions, (a) CO_2 emissions from energy and industrial processes, (b) CO_2 emissions from AFOLU, (c) CH_4 emissions, (d) N_2O emissions. The box represents the interquartile range with the median represented by the solid horizontal line. The whiskers represent the full range across the corresponding pathway class.

CO_2 emissions from AFOLU (*Figure 2b*) show a large variation in the SR1.5 pathways. Most infilled scenarios cluster in the interquartile range of the high-overshoot and 2°C scenarios, with the reported 2050 value from Shell a high outlier and implying a heavy reliance on land-based CDR that goes well beyond most of the low- and high overshoot pathways. Due to the overlapping ranges between the different pathway classes (e.g., high overshoot characteristics overlap with the low overshoot characteristics), it is not sufficient for a pathway to be located in the low overshoot CO_2 emission range to assess its compatibility with the Paris LTTG.

Climate categorization and properties of scenarios

Most of the scenarios we assess here overshoot the 1.5°C warming limit by a significant margin (*Figure 3c*). Equinor's Rebalance scenario peaks at a median warming of 1.73°C above pre-industrial (here 1850-1900 is used as a proxy for pre-industrial) levels in 2060, and a similar margin of overshoot is observed in BP Rapid (1.73°C in 2058), Shell Sky (1.81°C in 2069) and the IEA SDS (1.78°C in 2056). All of these scenarios would be classified as "Lower 2°C" pathways and are inconsistent with the Paris LTTG, failing to hold warming well-below 2°C (nor pursuing 1.5°C). BP's Net Zero scenario results in a median end of century warming of 1.5°C (consistent with the scenario claim), the high temporal overshoot (median peak warming of 1.65°C) results in the pathway being classified as a '1.5°C high overshoot' pathway. The one exception to note is the recently-released IEA NZE scenario which we assess as a '1.5°C low overshoot' scenario. This scenario has the lowest maximum peak exceedance probability, and we assess it to be close to meeting the condition of being 'very likely less than 2°C' (>90% likelihood).

A key potential source of uncertainty, even with our internally consistent method, is in regards to the climate categorisation due to different infilling methods. Among the five scenarios with a large number of gases infilled (Shell is omitted here), four are situated in the same climate category irrespective of the infilling method (see *Supplementary Table 4*). One scenario (IEA NZE) would be situated in a higher climate category (1.5°C high overshoot) when the RMS method is applied – we trace this back to the specific characteristics of the pathway selected to infill under the RMS method. This uncertainty can be reduced by more complete multi-gas modelling, with non-CO_2 emissions assessed in a manner consistent with the actual production of fossil fuels, biofuel production, among others.

Table 1 *Key climate outcomes for assessed institutional pathways using the QRW infilling method*

Source	Scenario	Median Level of Peak Warming	Median Year of Peak Warming	SR1.5 Climate category	P1.5°C Max (2100)	P2°C Max (2100)
Equinor	Rebalance	1.73°C	2060	Lower 2°C	78% (64%)	23% (20%)
Shell	Sky	1.81°C	2059	Lower 2°C	86% (60%)	29% (17%)
BP	Rapid	1.73°C	2058	Lower 2°C	78% (61%)	23% (18%)
BP	Net zero	1.65°C	2049	1.5°C high overshoot	71% (36%)	16% (9%)
IEA	SDS	1.68°C	2056	Lower 2°C	73% (55%)	19% (14%)
IEA	NZE	1.56°C	2045	1.5°C low overshoot	58% (18%)	11% (4%)

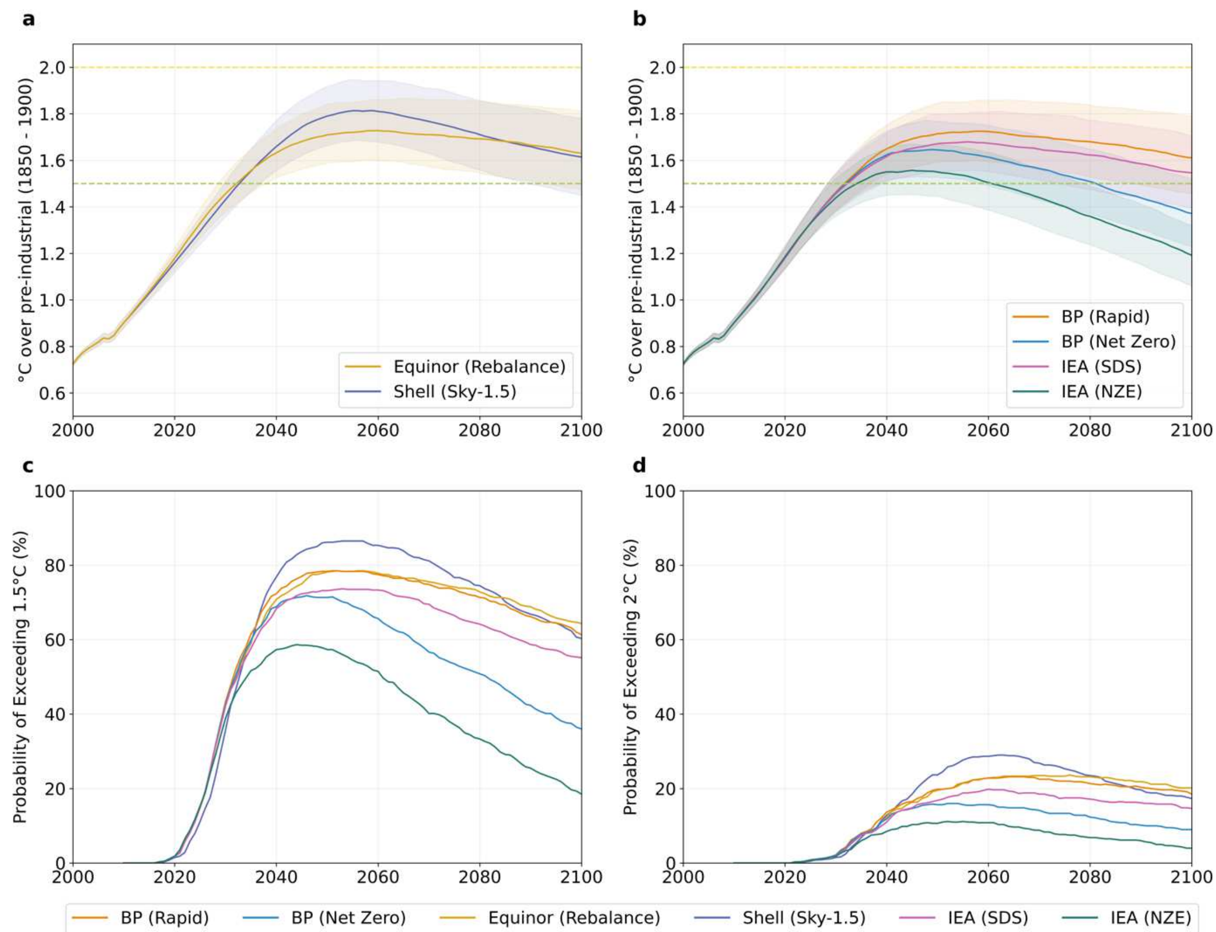

Figure 3 *Climate assessment of the institutional scenarios using MAGICC6. (a) and (b) temperature rise above 1850 – 1900 (the solid line is the ensemble median and the plumes are the 33rd – 66th percentile), (c) Probability of exceeding 1.5°C, (d) Probability of exceeding 2°C.*

Comparing technology-agnostic mitigation levers

Whether a given scenario will achieve the aim of the Paris Agreement is a strong function of the underlying energy system transformation. Warszawski *et al*.,[22] (2020) propose a set of mitigation levers that can be used to compare the mitigation options selected by different pathways[22]. These include CDR deployment, changes in energy intensity of final energy (CI_t), change in energy demand (E_t) and relative reduction in non-CO_2 emissions (all reductions relative to a base year, which the authors select as 2018). We select 2010 as the base year for comparison, and the indicators CI_t and E_t in 2030 and 2050 with respect to that base year to evaluate the energy system mitigation characteristics (*Supplementary Table S5*). We do not include scenarios from BP in this comparison because they do not report Final Energy in the data they make available. Since we have used the infilling methods to complete the set of greenhouse gases in the institutional pathways, it would be inconsistent to then evaluate those indicators against the non-CO_2 and non-energy-system emissions levers.

Final energy and the carbon intensity of that energy behave independently as levers that can both be used to reduce emissions. For example, the Equinor Rebalance and the IEA NZE scenarios have final energy demand consistent with the range of 1.5°C compatible SR1.5 scenarios at about 90% of the 2010 level, illustrating the increasing importance of energy efficiency, whereas Shell Sky 1.5 has a demand 50% higher than the SR1.5 scenarios. On the other hand, the carbon intensity in Rebalance is much higher, as is that of Shell Sky 1.5, in line with 'higher 2°C' pathways and approximately 40% of the 2010 CI, rather than 5-10% as in SR1.5 PA-compatible scenarios. Only the IEA NZE scenario has both E_t and CI_t consistent with low overshoot pathways both in 2030 and in 2050.

Comparing technology preferences across the pathways

The speed and depth of transformation in the electricity sector provides a significant indication of potential achievement of a temperature goal, given that all other energy sectors depend to a greater or lesser degree on electrification. In IAM scenarios there is a clear relationship between the share of coal that remains in electricity generation and the temperature categorization, although in all cases coal generation decreases strongly (*Figure 4a*). The Equinor and Shell scenarios tend to match more closely the remaining coal generation of the higher-temperature IAM scenarios; the BP Net Zero scenario has more coal generation in 2030 than the PA-compatible IAMs, although it converges to those scenarios by 2050. This latter feature indicates a somewhat slower transition away from coal and helps explain the categorization as non-PA-compatible. The IEA NZE scenario shows the most similar behavior to the IAM scenarios that are PA compatible, most closely matching low-overshoot scenarios in 2030 and then below-1.5°C scenarios in 2050.

In the case of natural gas, results shown in Figure 4c indicate that those scenarios closest to Paris Agreement compatibility also tend to be those with the most rapid decrease in natural gas shares in electricity generation, including the IEA NZE scenario. However, the range of use of natural gas is large, depending on scenario and model, and therefore reflects the uncertainty in the literature as to the 'bridging' role for natural gas in the power sector[23–25] . Part of this uncertainty is due to the potential in some models for significant fossil-fuel carbon capture and storage potential. Given that levelized costs of solar PV and onshore wind are already cheaper in many regions of the world than new fossil fuel based electricity generation even without the additional costs of CCS, economic decisions about low-carbon sources are likely to favor the former[26].

On the other hand, IAM scenarios with low- or no-overshoot tend to have lower levels of wind and solar share in electricity generation in 2050 than do the IEA NZE, Shell Sky and BP Net Zero scenarios (~45% vs. 60%-65%), possibly reflecting a historical tendency of IAMs to underestimate the potential for higher shares of variable renewable energy[27–31]. All models tend to show similar characteristics for nuclear power by mid-century with a share in electricity generation somewhat lower than at present, but higher in absolute terms due to the increasing contribution of electricity in the energy system (*Figure 4f*, compared to *Figure 4e*), with primary energy either decreasing or growing only slightly by mid-century in 1.5°C compatible scenarios.

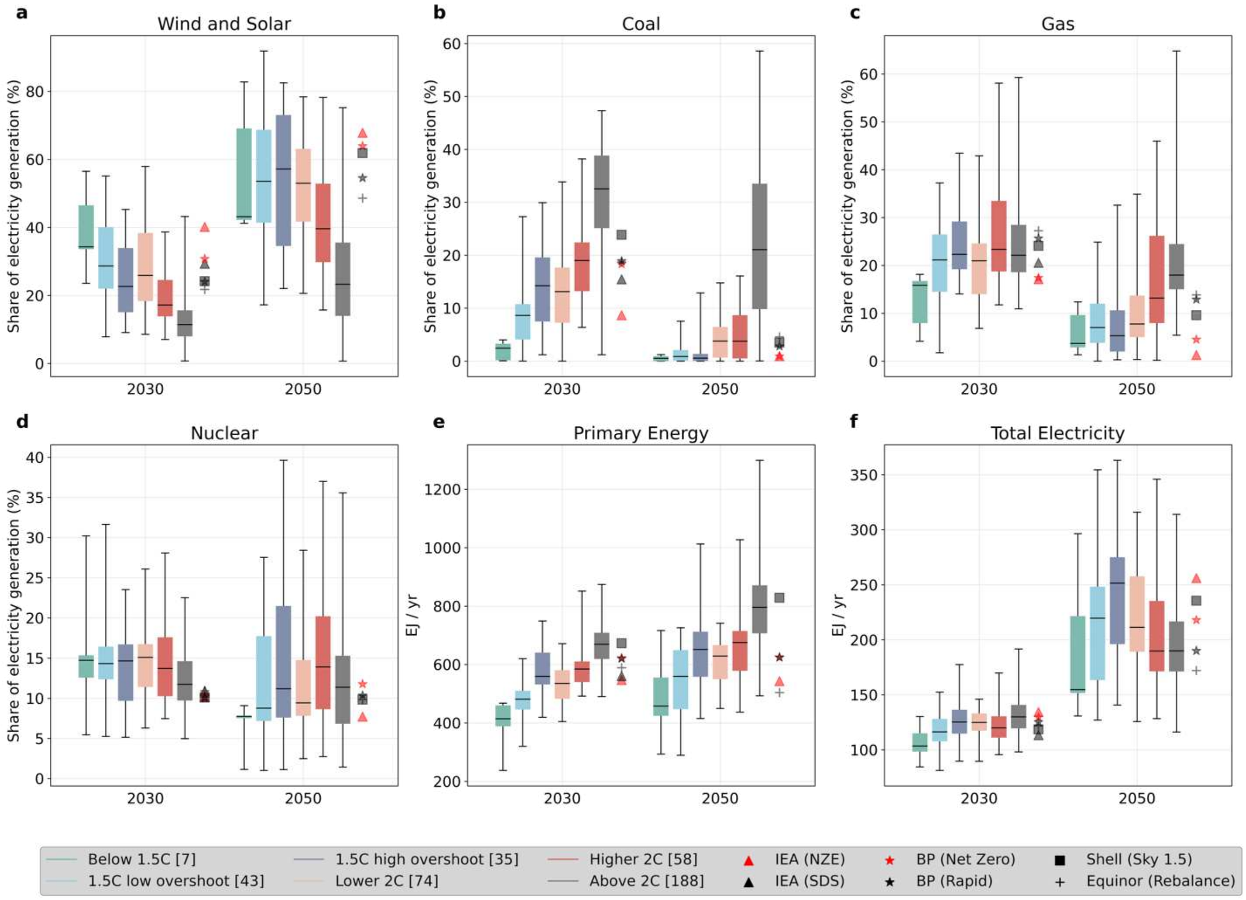

Figure 4 *Key energy system characteristics across pathways. (a) Share of coal in electricity generation, (b) Share of natural gas in electricity generation, (c) Share of nuclear in electricity generation, (d) Share of wind and solar in electricity generation, (e) Primary energy, (f) Total electricity*

Implications for mitigation scenario development and decision-makers

The Paris Agreement sets not only a long-term temperature goal, but also intermediate conditions constraining allowable temporary overshoot of 1.5°C. More recent literature also introduces a further bound on the energy system transformation through sustainability limits on the potential for deployment of bioenergy with carbon capture and storage (BECCS) and of carbon-dioxide removal (CDR)[7,32–38]. Pathways that delay reductions in fossil fuel consumption in the near-term and thus lead to a high overshoot of 1.5°C run the risk of counting on an over-dependence on CDR later in the century. In addition, anthropogenic greenhouse gas emissions beyond CO_2 must be reduced as well; in some cases, such as with some methane emissions, this will tend to occur along with the reduction in combustion or recovery of fossil fuels. However, emissions from agriculture, such as methane and N_2O will require mitigation as well.

Since normative scenarios relevant to the Paris Agreement and published by institutions such as the IEA and fossil fuel companies provide important input to policymakers and investors, they should provide a complete pathway to the end of the century for all GHG emissions for all sectors so that temperature assessments can be made. A methodology for evaluating total GHG and aerosol precursor emission pathways is presented here in a manner that allows intercomparisons even in the absence of such provided pathways, while acknowledging the uncertainties inherent in using such techniques. Published institutional pathways that do not actually lead to the LTTG of the Paris Agreement will likely provide a misleading view of the transformations needed for reducing GHG emissions both in the near-term and the long-term.

For the most part, the institutional pathways analyzed here do not achieve the Paris Agreement LTTG, or do so with substantial interim overshoot. Primarily, this is due to a continued reliance on fossil fuels that is greater than IAM pathways that achieve the PA goal. For example, although the use of coal shows a steep decline in all pathways, it is notable, and of particular importance for policymakers and for investment decision-making, that the role of natural gas is less clear, demonstrating a large range of uncertainty in the various pathway categories. In general, though, pathways that achieve the PA LTTG without significant overshoot do not appear to allow for a bridging role for natural gas; however this is an area ripe for further investigation.[39–41] On the other hand, some of the institutional pathways indicate the potential for higher and faster penetration of renewable energy uptake than do many IAMs, also an important signal for discussions about meeting the PA LTTG.

Our focus has been on institutional pathways, but similar limitations are valid for the growing literature of bottom-up energy modeling approaches that find the potential for 100% renewable energy based systems by mid-century[42–51], which tend to outpace estimates of renewable penetration rates compared to IAMs [27,52,53]. A claim of 100% RE by 2050 may align with power-sector benchmarks for PA-compatibility, but it is not sufficient to guarantee these pathways meet the LTTG. They should also be self-consistently evaluated by including full GHG pathways. The trend in the scientific community is towards full data and model transparency, an increasingly important part of the science-policy interface. In the case of claims on pathway compatibility with international climate agreements, this transparency should extend to the data and assumptions required to confirm such statements.

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Methods

Data Sources and Handling

In this study, we construct a harmonized dataset of institutional scenarios and compare them with the scenarios underlying the Special Report on 1.5°C (SR1.5). For this, we harmonize all emissions to 2010 values in line with the approach adopted in SR1.5 - we use historical data from the SSP database[54] and harmonized scenario data[55,56]) from the SR1.5 scenario database hosted by IIASA[9]. In this work, we assess normative scenarios (*i.e.*, scenarios that claim to reach a Paris Agreement future) from four institutions: Equinor, the International Energy Agency, Shell and BP. For scenarios where data for 2020 are not available, we extend the data series to 2020 based on the historical trend observed in the data reported by the study. We note that this does not account for the effect of COVID-19 on emissions; however, the IEA projects a strong growth in emissions in 2021 and hence the bias induced by this assumption (in one year) is unlikely to affect our assessment. To fill in missing gases, we use CO_2 emissions from energy and industrial processes as the lead gas. Scenarios from Equinor and BP do not report industrial process emissions. For these scenarios we assume that industrial process emissions follow the same trajectory as the IEA Sustainable Development Scenario (SDS).

Harmonization

We harmonize all emission trajectories to the 2010 values from our historical dataset using the harmonization package aneris[57]. We select a constant ratio harmonization method, with the ratio (between the historical data and the scenario data in the base year) converging to 1 in the last available scenario year. For the Shell scenarios that report data until 2100, we use the default method selected by *aneris* (reduce ratio to 2080), which is the default adopted in the CMIP6 emission harmonization routines[58].

Extending Series Until 2100

Published scenarios from IEA, Equinor, and BP have data to 2040 or 2050. We extend these data from the last available scenario data point to 2100 using the Constant Quantile Extension (CQE) method[16] and implemented in the Python package *silicone*[59]. We first identify the position (quantile) of the scenario emissions in the last available year with respect to an underlying distribution of emission pathways. We then apply the same quantile to the emission distribution to extend the scenario emissions until 2100. In this paper the underlying emission distribution is drawn from the database of scenarios underlying the Special Report on 1.5°C[9,60]. With the CQE, we attempt to capture some element of the underlying model dynamics while extending the pathway. A drawback of this method is that the underlying distribution of emissions may not represent structural transition in the energy system models (used by the three institutions) appropriately. To evaluate the validity of the method, we assess its effectiveness in reconstructing known data (here, data from the SR1.5). We truncate each pathway (*i.e.*, model and scenario combination) in the SR1.5 database at 2050 and then use the CQE method to extend the pathways to 2100. We then calculate the root mean square difference between the original value and the extended value in each time step, normalized by the spread of values in that time step, defined by:

$$\epsilon = \Sigma_i \sqrt{\Sigma_t \frac{(p_{i,t} - q_{i,t})^2}{n_t \, \sigma_t^2}} / n_i$$

where ϵ is the error, $p_{i,t}$ is the CQE-extended value of pathway i at time t, $q_{i,t}$ is the originally projected value at that time, $n_{i\,(t)}$ is the number of pathways (times) being summed over and σ_t is the standard deviation of original projections at that time. This effectively compares the error when using the CQE method with the error from using the average value in the database at that time – a value of one corresponds to the error in using the average value in the database at each time. The results of this method being applied to various emissions types can be found in **Supplementary Table S1**. For CO_2 emissions from energy and industrial processes, the error measured this way is 0.22 indicating that this method, for the dataset considered here, is far better than simply using the average value from the database.

Gas Infilling

Gas infilling (*i.e.*, inferring missing emission species) is necessary to construct a complete, multi-gas emissions trajectory that can be used to assess the climate impact of a scenario. In this paper, we apply the infilling approaches implemented in the Python package silicone[59] . The key premise of the infilling techniques is that there is a relationship between the emissions that are represented in the scenario and emissions that are to be inferred - the different infilling methods correspond to different ways of defining that relationship. In the main body of this paper, we use the 'Quantile Rolling Windows' (QRW) technique to infer missing emission species. We use CO_2 emissions from energy and industrial processes (Emissions|CO2|Energy and Industrial Processes) as the lead gas consistently. We provide a short description of the QRW infilling method here, as a summary of the published methodology[59]. In the QRW method, a weight of $\frac{1}{(1+(lead\ value\ difference)^2)}$ is applied to all data points at equally spaced data points across the infiller lead. Then, the median of the follower value at these points is selected and returned. The QRW technique gives the best balance between robustness to small changes and accuracy in infilling results. We use it here in preference to the RMS closest technique, which is slightly more accurate when applied to the SR1.5 database but more variable, and as a whole-pathway technique means that the values at one time are influenced by values at another. This latter feature is best avoided when we are using techniques to project emissions forward in time from an earlier stage. For those scenarios that report 2020 emissions that account for the impact of the COVID-19 pandemic, we include the reported 2015 value to reduce the bias introduced by interpolating between 2010 and 2020 (this applies to Shell Sky and IEA NZE). We assess sensitivities to two other common infilling methods that have been used in the literature (the 'Equal Quantile Walk' and 'RMS pathway matching' methods.

Climate Assessment

To assess the climate impact of the scenarios, we provide the constructed multi-gas emission pathways as an input to the reduced complexity carbon cycle and climate model MAGICC6[20] using a Python-based wrapper Pymagicc[61] to process the data. The probabilistic distribution of climate impacts is assessed using 600 sets of parameters that reflect the climate sensitivity range assessed by the IPCC in the 5th Assessment Report and the Special Report on 1.5°C, as well as to represent carbon cycle uncertainties. Updated distributions, in line with the forthcoming 6th Assessment Report of the IPCC or more recent literature may lead to different conclusions about the climate implications of these scenarios. We calculate the temperature rise relative to the 1986 – 2005 mean value and add 0.61°C to make the comparison relative to the 1850 – 1900 reference level. This follows the approach from AR5[62] (Chapter 6,

Figure 6.12 – 6.13) that was subsequently used in the SR1.5. The categorisation follows the categories in SR1.5 that are described in further detail in *Supplementary Table S3*.

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Author Contributions

RJB, MJG, BH and MS conceived the research and analysis. GG, RJB and ZN carried out the analyses. GG, RDL and ZN performed sensitivity and robustness analyses of results. MM leads the development of MAGICC and created the climate parameter configuration used in this study. ZN, RDL, JL, and MJG developed and maintain software utilized by the methodology used in this study. RJB, GG and MJG developed the rough draft of the manuscript. All authors contributed to the submitted manuscript.

Code and Data Availability

The software and scripts we used to perform this analysis are available at: https://gitlab.com/gaurav-ganti/institutional_scenarios. The repository will be made available over the course of the review process and will be made available as requested to reviewers.

Competing Interests Statement

The authors NO competing interests.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

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