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Research article

Electricity climate-compatibility index: Measuring global progress towards decarbonising the power sector

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ABSTRACT

This paper proposes a novel index, ECI (Electricity Climate-Compatibility Index), to measure global fossil fuel electricity generation alignment with climate targets. Net anthropogenic carbon dioxide emissions (CO_2) must approach zero by mid-century to stabilise the mean temperature to well below 2°C. Pursuing carbon neutrality will require immediate action if we are to avoid the economic risks associated with a delayed, more abrupt energy transition. This paper reviewed the existing literature and found insufficient indicators for country-level climate targets in electricity generation. Therefore, the paper proposes a novel electricity climate-compatibility index (ECI) to address the gap. The index computes climate compatibility or incompatibility as the difference between fossil fuel electricity generation permitted in the Integrated Assessment Model (IAM) country-level climate scenarios and that which is generated from operational, under-construction and planned power generation assets. The ECI correlates positively in specific instances with relatable metrics such as Energy Transition Index (ETI) and Climate Change Performance Index (CCPI) but provides a better understanding of the climate-incompatible generation of fossil fuel plants for a decarbonised power sector.

1. Introduction

In this paper, we investigate whether an index can be used to measure global progress toward emission neutrality in fossil fuel (FF) electricity generation. Specifically, the electricity climate-compatibility index (ECI) developed in this paper offers the first global country-level indicator to measure climate compatibility in the power sector to the author's knowledge. ECI serves to inform policymakers, investors, corporates, and researchers of the impact of existing, under construction and planned FF power generation assets on realising climate goals. Utilising indicators to convey energy transition patterns and concerns to policymakers and the general public has been commonly used in the past (see Patlitzianas et al., 2008; Gunnarsdóttir et al., 2020; Kruyt et al., 2009). A well-constructed indicator or group of indicators translates the basic statistical information into a more profound knowledge of a problem to contribute to the development of a comprehensive image of the entire system, including its interdependencies and trade-offs (Gunnarsdóttir et al., 2020).

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Here, we pool 170 countries globally and use downscaled country-level climate scenarios from the power sector - assessing them against existing, under construction and planned FF power generation assets. This novel approach is driven by the uncertainty associated with the pace and scale of the energy transition. It shifts the discussion to evaluate climate-aligned pathways for electricity generation assets and whether they are subject to an intensified risk of stranding effect if no mitigation measures are implemented. For instance, \$2.1 trillion worth of electricity generation assets must be revised for abatement measures by 2050 to prevent a global warming disaster (Krishnan et al., 2022).

1.1. The energy transition, climate and unabated stranded assets

The energy transition requires significant structural change that takes existing energy systems to a new paradigm driven by rising climate change threats and the innovation of emerging technologies (Carley and Konisky, 2020). The complex and sophisticated nature of the transition denotes the necessity to consider existing and planned assets in energy transition-related decisions. In the last decade, an evident expansion of fossil-fuel assets was observed and exceeded \$110 billion in 2020, leading to the probable exhaustion of carbon budgets if no abatement measures are considered, particularly in coal and oil-powered assets (IEA, 2020). Thus, stranded asset concerns emerge when governments and businesses decide on the pace and scale at which they decarbonise and strategies to adapt toward a just transition (Markard, 2018).

Climate-compatibility encourages investments and development to address the environmental impact and externalities of anthropogenic climate change (Mitchell and Maxwell, 2010). However, being positioned as climate-incompatible can result in a rising risk of climate threats and stranded assets. According to the International Energy Agency (IEA), the term 'stranded assets' describes "those investments which have already been made, though at a point in time prior to the end of their economic life (as assumed at the investment decision point), are seen to no longer earn economic returns as a result of changes in the market and regulatory environment brought about by climate policy" (IEA, 2013). Hence, climate-incompatibility leads to elevated risk exposure toward asset stranding.

Numerous factors lead to the stranding effect of assets. For example, Green (Green and Newman, 2017) argues that stranded assets emerge from disruptive innovations, while Caldecott (Lu et al., 2022) indicates they emerged due to climate policies. However, the growing climate pledges and target observations suggest that various climate policy forms are pipelined for implementation, resulting in an amplified exposure risk for unabated and undiversified electricity generation asset portfolios (Curtin et al., 2019). Henceforth, the stranding effect emerges as a new risk, particularly for those countries adapting their power generation portfolios toward highly pollutant fuels (i.e., coal-fired assets). In this paper, we shed light on the climate alignment of power generation assets and investments and review the literature to address relevant gaps fulfilled by the paper.

1.2. Review of relevant literature

The concept of stranded assets due to climate-incompatibility led to a wide range of research over the last few years. A selected number of these studies were extracted and categorised in Fig. 1. The 3 × 3 matrix classifies based on two essential categories. First is the depth of geographic coverage, whether based on national, regional, or global country-level analysis. Second is the addressable side of the energy supply chain, whether it is upstream (reserves and extraction assets), downstream (refineries and power generation assets), or both (i.e., integrated).

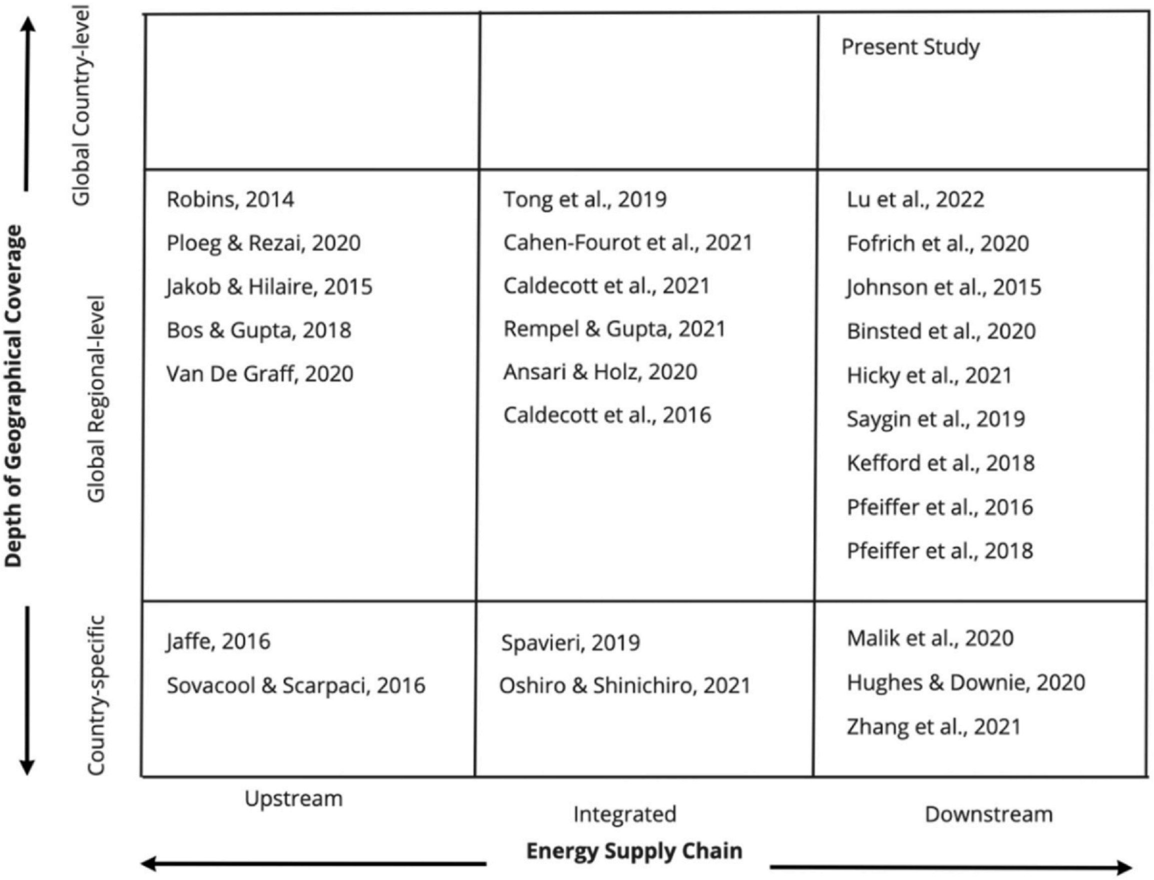
In Fig. 1, upstream studies follow the narrative on "unextractable reserves" based on climate constraints to maintain temperature rise to well below 2°C. In contrast, the literature on downstream applications is almost predominantly power sector-related. This is mainly for the case of highly pollutant, and unabated coal power plants since continuous investments in these assets are still observed (Lu et al., 2022; Fofrich et al., 2020; Saygin et al., 2019). Other studies include upstream and downstream assets and are generally classified as holistic energy systems analyses.

Generally, publications range from case studies on a national level to a global scale. However, the coverage in national studies focuses predominantly on China and India – owing to rising investments in unabated coal assets. In contrast, regional studies concentrate on parts of Asia, Europe, Latin America, and the Middle East & North Africa (MENA). Others cover organisations or collations such as OPEC or G20 (Graaf, 2018; Saygin et al., 2019).

For an asset to become exposed to stranding risks, several drivers contribute to arriving at such an outcome. In the review of the literature, these are largely environmental or climate-related. This is mainly due to an alarming rise in global mean temperature, leading national and international players to make appropriate intervention policies. However, there are other non-climate-related drivers, such as market changes, volatile prices and disruptive technologies.

1.3. Gap analysis

The trend for many published studies follows a similar narrative; the longer the remaining life for unabated FFs assets and the more investments are made, the higher the likelihood of unmet climate targets. However, there is insufficient evaluation of the climate alignment of countries in the electricity sector. Ansari (Ansari and Holz, 2020) created an index identifying FF sectors most prone to stranding effects across three regions. Although the index accounts for FF sectors, it does not explicitly account for power generation assets nor segregate which countries in these regions are likely to meet their climate commitments. Other studies, including Fofrich (Fofrich et al., 2020) and Saygin (Saygin et al., 2019), assessed the retirement rates necessary to maintain different climate pathways and future electricity demand globally at a regional level. However, the analysis is broadly high-level and does not



	Upstream	Integrated	Downstream
Global Country-level			Present Study
Global Regional-level	Robins, 2014 Ploeg & Rezai, 2020 Jakob & Hilaire, 2015 Bos & Gupta, 2018 Van De Graff, 2020	Tong et al., 2019 Cahen-Fourot et al., 2021 Caldecott et al., 2021 Rempel & Gupta, 2021 Ansari & Holz, 2020 Caldecott et al., 2016	Lu et al., 2022 Fofrich et al., 2020 Johnson et al., 2015 Binsted et al., 2020 Hicky et al., 2021 Saygin et al., 2019 Kefford et al., 2018 Pfeiffer et al., 2016 Pfeiffer et al., 2018
Country-specific	Jaffe, 2016 Sovacool & Scarpaci, 2016	Spavieri, 2019 Oshiro & Shinichiro, 2021	Malik et al., 2020 Hughes & Downie, 2020 Zhang et al., 2021

Fig. 1. A review of selected publications on the stranding risk of assets due to climate incompatibility, classified by the depth of geographical coverage and energy supply chain. The criteria selection is towards those most applicable to climate and emissions research. The energy supply chain starts from studies focusing on reserves (upstream) to those focusing on conversion (downstream) or both (integrated). The depth of geographic coverage refers to the number of countries included in the study, whether a single country (national), a select few (regional) or worldwide (global). Robins (2014); Van der et al. (2020); Jakob, Hilaire (2015); Bos, Gupta (2018); Cahen-Fourot et al. (2021); Caldecott et al. (2021); Rempel, Gupta (2021); Caldecott et al. (2020); Johnson et al. (2015); Binsted et al. (2020); Hickey et al. (2021); Pfeiffer et al. (2016); Jaffe (2020); Sovacool, Scarpaci (2016); Spavieri, Simonetta; Oshiro, Fujimori (2021); Malik et al. (2020); Hughes, Downie (2021); Zhang et al. (2020).

distinguish the assets on a country level. In other papers, Lu (Lu et al., 2022) and Kefford (Kefford et al., 2018) attempt to conduct a regional analysis to estimate whether FF power generation assets would be climate-compatible with or without abatement measures; however, the analysis does not go beyond the estimate of stranded assets collectively.

Here we introduce a novel electricity climate-compatibility index (ECI) measuring global country-level progress toward carbon neutrality in the power sector. We follow a rigorous approach by assessing operational, under construction and planned FF power generation assets to account for their remaining generation compared to allowable generation stated by decarbonisation pathways in the electricity sector. The findings from the ECI are utilised to classify countries as per their perspective category. The classification informs the state of affairs in 170 countries listed in the IAM country-level climate scenarios, along with their progress aligning with climate targets.

The remainder of the paper and its objectives proceeds as follows: first, an elaboration on power plant unit-level data and climate scenarios are provided, together with an explanation of the methodological approach used to develop the index. Subsequently, the paper merged the findings from operational, under-construction and planned assets to estimate ECI. Next, the index classifies countries by those likely to meet their decarbonisation targets by evaluating climate-incompatible generation. Finally, the paper concludes on whether the index can denote countries' progress toward climate alignment.

2. Methodology

In this section, the paper begins by exploring the datasets used in this work, specifically focusing on the merged asset-level databases and climate scenarios. Secondly, the methodological approach is presented, followed by the estimation of the remaining generation of operation, under construction and planned power plants, in addition to incorporating climate scenarios and development of ECI. Finally, the last section sheds light on the limitations of this work and the application of CI as an indicative metric for countries' progress towards aligning with climate scenarios. Fig. 2 below shows the workflow to develop the ECI.

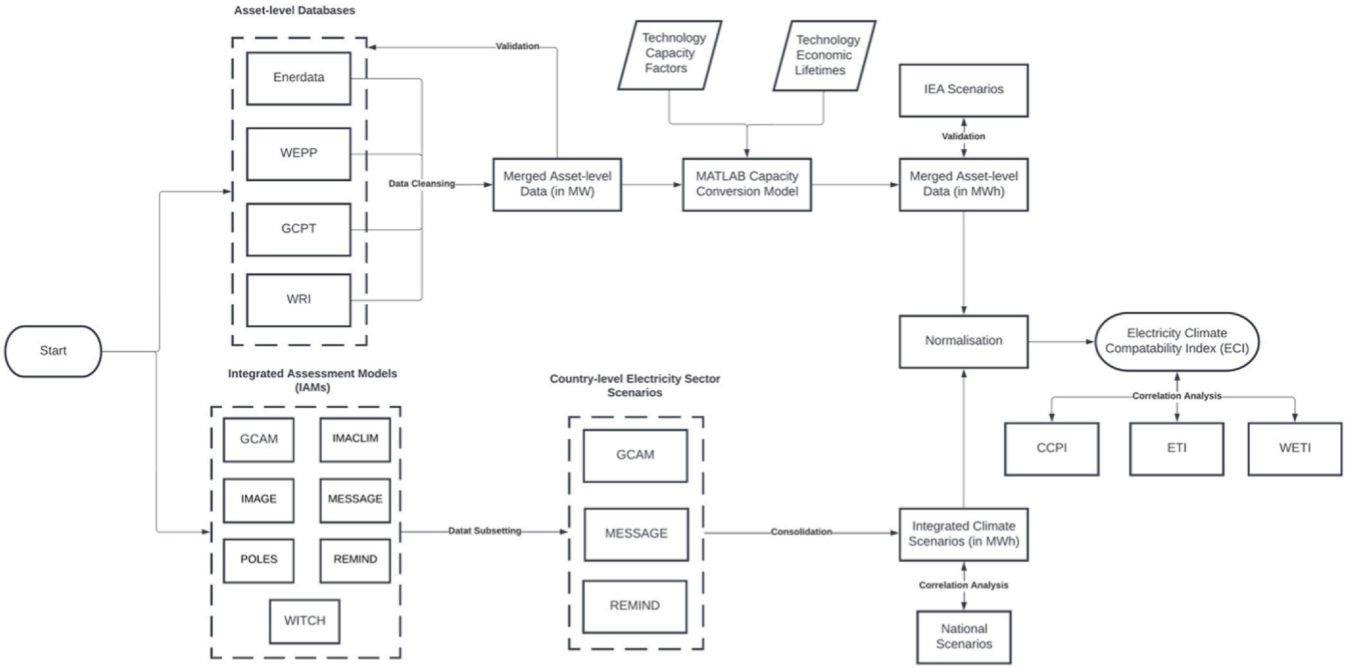


Fig. 2. A workflow for developing ECI using asset-level databases and Integrated Assessment Scenarios (IAMs). The ECI comprises two primary datasets: asset-level data and country-level electricity sector climate scenarios. We apply capacity factors and lifetimes assumptions to convert the capacity data of asset-level data set to generation using a MATLAB conversion model. We also consolidate various country-level IAM scenarios to develop climate-compatible generation. The results of both workstreams are then normalised to develop into ECI, detailed in the subsection below.

2.1. Global power-plant asset-level data

We utilise a dataset that includes existing operating and under-construction power plant assets and those planned, e.g., under bidding status or project agreement. The power-plant asset-level data is compiled by merging four databases to ensure comprehensive coverage. These include; (i) Enerdata Power Plant Tracker (EPPT) (ENERDATA, 2020), (ii) S&P Global Platt's World Electric Power Plants (WEPP) (2020) (S&P Global Market Intelligence, 2020), (iii) Global Coal Plant Tracker (GCPT) (2019) (Endcoal, 2019), and finally (iv) WRI global database of power plants (2019) (World Resources Institute, 2019). Compiling those databases compensates for incompleteness within different databases. For example, a significant number of missing commissioning dates were observed in the WRI database, particularly for power plants constructed in 2020. This was compensated by incorporating EPPT, WEPP and Coal Power Tracker. A high-level overview in supplementary table 1 shows key parameters of the asset-level data. The total operating capacity is estimated to be 6944 GW for 225 countries, covering roughly 97% of the global power capacity stated in the IEA World Energy Outlook (IEA, 2021).

The units from WEPP, WRI and GCPT databases above were merged by (Lu et al., 2022). These results were complemented with the incorporation of EPPT to account for missing commissioning dates of power plants. All four datasets were merged manually by confirming and validating the power plant name, owner, capacity, commissioning date and location. The commissioning date here refers to the date the plant started operating. We complement our dataset with manual online searches where required, particularly for commissioning dates since most power plants are deployed in stages with unit capacity increments. This is particularly the case for operational power plants, as more than 74% of existing FF power generation assets are expected to be decommissioned by 2050. The dataset was also examined to omit any delayed, cancelled, withdrawn or abandoned power plants as per the updated databases from EPPT and WEPP.

The databases were later classified into operational, under construction and planned assets. For operational assets, 0.1% of missing commissioning dates information was observed and was manually compensated by filling in and addressing missing values. For under-construction and planned assets, we observed that commissioning dates were more certain for those assets under construction than those under planning status. The underlying reason is that 'under construction' assets have already been committed, unlike those assets 'under planning' since they have a higher likelihood of being cancelled, delayed, withdrawn, paused, or abandoned since no capital has been invested in most cases. However, precise commissioning dates for under-construction and planned assets are not necessary since they are expected to remain online well beyond many climate targets in 2050 or 2060 as per their technical lifetime (assuming they are implemented as planned).

2.2. Country-level climate scenarios

We use climatic scenarios from the NGFS database to forecast the evolution of power generation to the end of the century. The Network for Greening the Financial System (NGFS) is a group of central banks and supervisors to support the understanding of possible scenarios toward climate targets to transition toward a sustainable economy (Bertram et al., 2020). The NGFS Climate Scenarios are the product of three established integrated assessment models (IAMs): GCAM, MESSAGEix, and REMIND. These models have been widely used to inform policymakers and decision-makers. They are featured in many climate change assessment reports and risks associated with climate-incompatible portfolios, in addition to peer-reviewed journals, for example, (Lu et al., 2022; Bauer et al., 2012, 2016; Bertram et al., 2015; Creutzig et al., 2017). They are also one of the only country-level and sector-specific scenarios which allows multiple cases to be applied.

The Global Change Assessment Model (GCAM) is a global model that captures the interconnections and behaviour of five systems: energy, economy, climate, water, agricultural and land use (Calvin et al., 2019). With a "myopic" perspective of the future, GCAM employs a partial equilibrium model of the land use and energy sectors. At each time step, GCAM agents evaluate the past and present when formulating their behaviour, including their predictions for the future (Calvin et al., 2019). It is anticipated that current pricing and policies will endure for the duration of the capital investment, which can affect the investment dynamics of technologies, such as the deployment of carbon dioxide removal technology.

On the other hand, MESSAGEix is a general equilibrium model with inter-temporal optimisation (i.e., perfect foresight). It enables the models to forecast 21st-century developments accurately (e.g. increasing carbon prices, declining costs of solar and wind technologies, and increasing costs of exhaustible resources) (Krey et al., 2020). At its core, MESSAGEix employs a dynamic linear least-cost optimisation method to build the scenarios by meeting specified commodity and node demand levels at the lowest possible total cost. The goal function aggregates expenses and expenditures for each of the listed modules, including carbon taxes, electricity from renewables, investment and operation costs for energy assets, and costs for extracting depletable resources (Bertram et al., 2020).

Finally, REMIND (REgional Model of Investment and Development), similar to MESSAGEix, is a general equilibrium model that portrays the future expansion of the global economy, with a focus on the trends of the energy sector and its implications on the global transition (Luderer). The model determines the ideal mix of investments in each region's economy and energy sectors, given the climate, regulatory, demographic and technical constraints (Bertram et al., 2020). In addition, regional trade characteristics involving commodities, energy sources, and emission permits are considered.

The IAMs are based on a decarbonised power sector, an internationally agreed-upon goal for mitigating global warming in the second half of the century. The IPCC concluded that realising carbon neutrality is critically needed to remain consistent with the 1.5°C (IPCC, 2022). However, the estimates showcased in these IAMs are subject to considerable uncertainty (Schwanitz, 2013). Therefore, the total average for each country was taken for all IAMs to allow for a neutral and complementary estimation of the maximum amount of FF electricity generation necessary to be in line with a carbon-neutral pathway. In supplementary table 2, we highlight the main differences and characteristics of the three models used in this paper, while supplementary Fig. 3 shows the differences in country-levels.

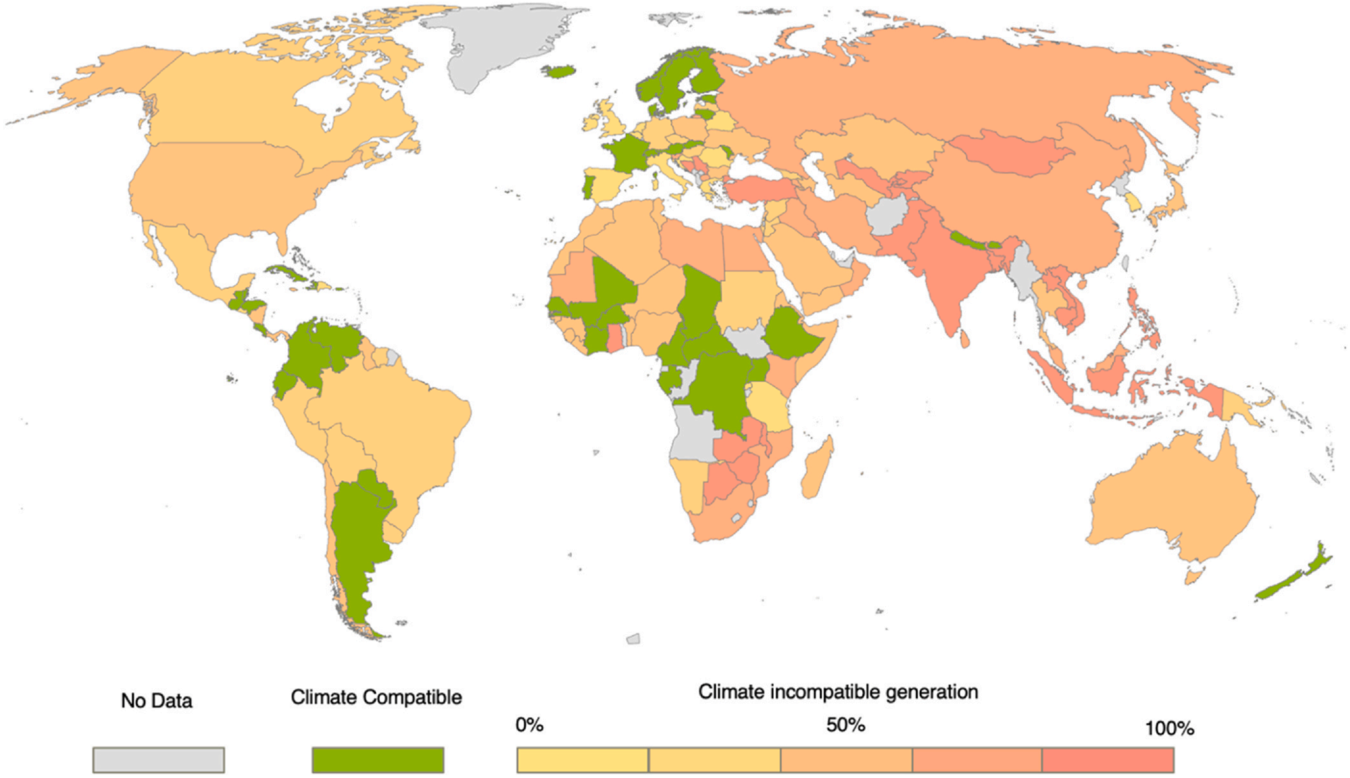


Fig. 3. The electricity climate-compatibility index (ECI). The green scale refers to countries which are likely to become climate compatible. Moreover, yellower countries have lower percentages of climate-incompatible generation, whereas those on the red scale will have tremendous deviations from climate policies by 2050.

NGFS IAM scenarios are country-level scenarios for electricity generation. Approximately 170 countries were downscaled in the IAM decarbonised power sector pathways at a national level by converting global scenarios into more granular country-level pathways to enable further analysis. A selection of essential variables, including primary energy, final energy and emissions, has been downscaled to the national level (Bertram et al., 2020). Each country begins with its current state and progressively converges to the IAMs-predicted regional trajectory. The convergence rate depends on country-specific institutional conditions (see supplementary table 3). The downscaling tool delivers results based on two types of data: 1) observed historical energy statistics at the country level and 2) regionally aggregated benchmarks from IAMs (Bertram et al., 2020). The downscaled data should be consistent with country-level observations in the short term. However, in the long term, energy variables converge toward regional IAM values and may diverge substantially from historical data. Therefore, in this study, we have focused on a relatively short-term horizon to estimate various countries' progress towards realising decarbonisation ambitions and the exposure of climate-incompatible generation.

2.3. *Methodological approach*

We use a three-step process to develop estimations for the ECI. First, we estimate the future energy production from operational, proposed, and under-construction power plants. Second, we compute climate-incompatible energy generation for each country as the difference between the climate projections and the FF electricity generation in the downscaled climate scenarios provided by various IAMs. Finally, we develop an index using climate scenarios and the total projected FF power generation for each of the 170 countries.

2.4. *Electricity generation*

The asset-level data highlighted in Section 2.1 shows total plant capacity but not generation. Here we convert the capacity data into generation to make estimates based on the generated power rather than what capacity has been installed. Different plants have varying generation profiles and characteristics. For example, coal, nuclear and some gas-fired assets often operate constantly or at baseload, not only due to their comparatively cheap operating costs but because they take time and resources to turn on, shut down, or adjust the operating level. Plant operators, therefore, restrict ramp-up and ramp-down occurrences accordingly. Other plants with shorter start-up and shut-down periods (e.g., open cycle gas-powered assets) are typically operated based on mid-merit or when demand surges.

In order to estimate electricity generation from the merged asset-level data, we follow a similar approach to (Pfeiffer et al., 2018), where an assessment of future electricity supply is conducted to be met from operating plants. For each country, the electricity generation is estimated for operating, under construction and planned assets as follows:

$$-G_{fcy} = C_{fcy} \cdot CF_f \cdot H- \tag{1}$$

G_{fcy} represents the total generation of fuel f in country c at year y, in megawatt-hours; C_{fcy} is the aggregate capacity of all plants with fuel f in country c at year y, in megawatts, whereas H stands for total hours in a year. The primary unknown value, in this case, is the capacity factor (CF) for coal, oil and gas power plants which is evaluated in the subsequent subsection.

Capacity factor

A synthesis of the IEA World Energy Outlook 2000–2021 Scenarios took place to estimate the capacity factor for various FF-generating technologies. These scenarios include fuel-specific capacity factors for power plants. We assume that future trends will follow historical patterns (i.e., no climate constraints that would otherwise limit FF production) – this is consistent with many relatable publications, for example (Lu et al., 2022; Pfeiffer et al., 2018). In addition, the IEA's scenarios include current and stated policies scenarios in which the mean was used to ensure capacity factors are proximate to whether these countries implement stated policies or fall behind in their existing policies. The overall trends from 2000 to 2021 saw declining oil and coal capacity factors with slight growth for gas-powered plants. As shown in supplementary table 4, the baseline has been assumed to be 55%, 22% and 40% for coal, oil and gas-fired power plants, respectively, which has been compared and benchmarked against other literature (Lu et al., 2022; Pfeiffer et al., 2018).

Power plants lifetime

We begin by evaluating the remaining lifetime of operating assets. To compute, we need to evaluate two key variables. The first variable is the commissioning date or when plants went online. This information is generally available from the asset-level datasets or can be looked up manually if not available. The second variable is the lifetime of power plants. As part of this study, we are required to make assumptions about when power plants typically retire. About 6% of the power plants in the database have information on when they are expected to be retired. The model considers the lifetime of other similar units. Power plants are considered similar if they use the same fuel, unit technology, and steam type, are in the same capacity ranges, and begin operation in the same year. In supplementary table 5, a benchmark was developed to compare lifetime assumptions to those previously published in the literature. The typical lifespan estimated in the baseline is a 39-year lifespan for coal-fired power plants, while oil and gas-fired power plants have a 36 and 37-year lifespan, respectively. This compares reasonably to those published in the literature (Lu et al., 2022; Tong et al., 2019; IRENA, 2017).

2.5. *Electricity Climate-Compatibility Index (ECI)*

The climate-incompatible generation is expressed as the difference between operating, under construction and planned electricity generation of FFs and the allowable FF electricity generation by NGFS IAMs (i.e., GCAM, MESSAGE and REMIND) to reach carbon neutrality. Countries with generation equal to or less than an allowable generation (i.e., decarbonisation target) are considered climate-compatible. On the other hand, those who have FF electricity generation above allowable generation are considered climate-incompatible. We understand that various countries have varying degrees of transition paces and patterns. Therefore, the optimum approach is comparing how far they are from being carbon-neutral in their power sector.

To determine the ECI, we proceed as follows based on varying asset types:

$$-C_{cfy,\ current} = G_{cfy,\ operating} - S_{cfy} \tag{2}$$

$$-C_{cfy,\ committed} = (G_{cfy,\ operating} + G_{cfy,\ under\ construction}) - S_{cfy} \tag{3}$$

$$-C_{cfy,\ stated} = (G_{cfy,\ operating} + G_{cfy,\ under\ construction} + G_{cfy,\ planned}) - S_{cfy} \tag{4}$$

$$-\ \mathrm{ECI} = \frac{\mathrm{Ccfy,\ stated}}{(\mathrm{Gcfy,\ operating} + \mathrm{Gcfy,\ under\ construction} + \mathrm{Gcfy,\ planned})} \tag{5}$$

Where $C_{cfy,\ current}$, $C_{cfy,\ committed}$ and $C_{cfy,\ stated}$ represent electricity climate-incompatibility generation based on the number of assets considered (i.e., operating, under construction and planned) for fuel f in country c at year y (i.e. 2050). $G_{cfy,\ operating}$, $G_{cfy,\ under\ construction}$ and $G_{cfy,\ planned}$ are the electricity generation of power plants for fuel f in country c in year y. $S_{cfy,}$ on the other hand, represents the downscaled decarbonisation scenarios developed by the mean of all NGFS IAMs for fuel f in country c at year y. Finally, the ECI is calculated by normalising the amount of climate-incompatible generation and total FF electricity generation.

The level of uncertainty is amplified from current, committed to stated assets scenarios. This is because under-construction assets in the committed scenario are subject to project barriers, delays, or cancellations. Furthermore, planned assets have even more uncertainty since minimal or no capital has been invested. For this purpose, the ECI will also highlight the differences and similarities of countries, taking into consideration the asset status to present how countries' investment decisions can have a tremendous impact on their progress toward a decarbonised electricity sector.

2.6. Limitations

Although the index follows a rigorous approach to ensure all climate and generation parameters are accounted for, it must not be mistaken for a comprehensive climate tracking index scoring. Instead, it is a complementary singular representation of the climate discussions in electricity generation to better assess where various counties stand in relation to the energy transition and how they can better align their mixes toward climate compatibility while ensuring a secure and affordable electricity supply.

In addition, the index is based on databases dated 2020. Therefore, they do not account for more recent changes since the status of power plants globally is constantly changing and can affect the index score to an extent. However, the method used in this paper can be applied to newly updated datasets with a similar coverage ratio of assets and their commissioning dates - the merged unit-level databases covered 96% of global power capacity in 2020.

Besides, the capacity factors (i.e., the frequency at which a power plant operates over a specific period.) are assumed based on the synthesis of the IEA World Energy Outlook 2000–2021 reports showcasing the generation and installed capacities of power generation technologies globally. Therefore, using an average can underestimate or overstate the generation of FF power generation across certain countries, which can slightly affect the results. In this paper, we conducted a sensitivity analysis to measure the impact of the changes in capacity factors for the ECI, which can be viewed in Fig. 3 in the supplementary table.

Furthermore, it is worth noting that assets that have been investigated include unabated fossil-fuel assets. It is well-recognised that retrofitting FF power generation assets with carbon capture, utilisation, and storage (CCUS) technologies could ultimately contribute toward climate compatibility. However, certain climate scenarios do not consider CCUS in future mixes of FF power generation assets. Therefore, some of these climate targets tend to have much more apparent constraints on the amount of FF power generation to become climate compatible.

Moreover, the index results do not capture the implications of affordability and security of supply to reach the corresponding country classifications. The index simply attempts to estimate where countries stand in the energy transition, with the constraint being climate compatibility. Therefore, the insights generated should be used as part of the analysis and not a sole conclusion. This is because other considerations such as circular carbon economies (CCEs), electricity access and carbon-negative technologies can complement countries' efforts toward delivering clean, secure power at the lowest cost.

Lastly, the classification of countries should not lead to far-reaching conclusions on which countries will be climate-compatible but rather a rough estimate of where countries stand today as per their existing assets and planned investments. Moreover, there is notable uncertainty about whether the planned assets, in particular, are likely to go as planned since they are subject to cancellations or delays. The index is designed to further in-depth country-level energy transition analysis and evaluate asset-level national data. Overall, the results presented here should be complemented with an assessment of carbon-neutral pathways at the national level, considerations of policies and national model results, among others.

3. Results and discussion

In this section, the results of the ECI are presented. First, we begin by shedding light on where various countries stand regarding climate-compatibility in the power sector through percentiles. Second, we analyse various countries to evaluate how the ECI results correlate with existing affairs. Finally, we compute and contrast the ECI results across higher uncertainty of asset development and discuss the implication on

3.1. Electricity Climate-Compatibility Index (ECI)

The climate-compatibility index (ECI) classifies countries based on their progress towards achieving a decarbonised electricity sector using three primary asset statuses: operational, under construction and planned FF power generation assets. The countries in the higher percentile are not in line to adapt to their climate targets. They are likely required to rethink their investment decisions for planned assets or early retire inefficient and pollutant power plants that have recovered their investment. In contrast, those countries in the bottom percentile are likely to become climate-compatible if they continue to follow their investment patterns. A comprehensive list of countries and their perspective percentiles are listed in supplementary table 6.

The ECI results highlight several insights. First, we identify countries dependent on baseload low-carbon generation using hydro, geothermal, biomass or nuclear generally perform favourably (e.g., Norway, Iceland, Switzerland, Paraguay and France). This dependency on renewable or nuclear baseload generation assets meant that investments in unabated FF power generation (if any) were minimal. These countries are typically endowed with abundant dispatchable renewable or nuclear resources. For example, Iceland has almost a fully-decarbonised power sector. 99.98% of electricity production in 2020 came predominantly from hydro (70%) and geothermal (30%). According to Statistics Iceland, these resources supported a growing demand from 7958 GWh in 2002–17,680 in 2019 (Statistics Iceland, 2019). For future investments, Iceland is gearing towards utilising onshore and offshore wind generation assets due to its potential (with average wind speeds around 18 m/s), with a pilot project of 1.8 MW installed back in 2013 (Ragnarsson et al., 2015). Therefore, the intermittency will be mitigated by pre-existing baseload hydro and geothermal resources.

Second, the index also shows that selected countries with relatively low electricity access and power generation are performing relatively superior in the index, considering their renewable-based baseload power and minimal or no planned capacities (e.g., Chad, Cote D'Ivoire, Ethiopia and Cameroon). These countries are positioned to examine the least-cost pathways for electrification, which could be through solar home systems or other micro-grid applications. However, it is reasonable to argue that the priority should be tailored towards increasing electrification rates rapidly using any least-cost energy sources. However, these countries can generally tailor their investments toward climate-aligned energy sources. For example, Ethiopia has a 48.06% national electricity access with an installed power capacity of 4205 MW that consists of hydro (89%), wind (8%) and thermal (3%) (IEA, 2021). The dependency on renewable baseload generation is likely to continue, with 17,050 out of 17,637 MW power capacity investment dedicated to hydro (92%) and the rest to geothermal, wind and solar (8%).

Third, it has been observed that countries with relatively higher fossil fuel reserves (e.g., Saudi Arabia, Russia, Canada and the United States) are unlikely to reach carbon compatible share of FF power generation. This is mainly attributed to the economics and reinforcing loops of extracting and investing these resources locally for power generation. These fossil fuel-rich economies are likely to continue leveraging their existing assets, which lead to a significant portion of their fossil fuels exceeding climate budgets. For example, Saudi Arabia was classified with moderate climate incompatibility ranking 114 out of 170. Saudi Arabia's electricity generation is dominated by natural gas (60%), followed by oil (39%) and solar (1%). Around two-thirds of the FF power generation assets were constructed after 2000, and the fleet is of moderate age. The country continues to invest in unabated conventional power generation, with 12.7 GW likely to come online by 2025 compared with 4.9 GW for renewables. The number of unabated FF power plants and the inherent long life of these assets has shifted KSA's position slightly toward a more moderate ranking.

Finally, we observed that specific countries undergoing significant economic development are performing unfavourably. These countries (such as India, China, Indonesia, Bangladesh, Pakistan) have tremendous population and GDP growth and are constantly investing in capacity to meet the baseload demand despite growing electricity consumption. However, the business-as-usual for these countries denotes climate targets are unlikely to be met since most of the investments are coal-fired assets—for example, Bangladesh, which is ranked 168 of 170 countries in the ECI. The electricity sector in Bangladesh has been booming in recent years and growing at 5% per year on average in electricity generation, which led to almost 100% electricity access in 2022 (Amin et al., 2022). The growth was primely driven by gas and oil-fired power plants, which represent, together with coal, roughly 99% of the energy generation in 2019 (Das et al., 2020). These recent installations led to a relatively young FF fleet with a total installed capacity of 20 GW as of 2019 (Das et al., 2020). FFs account for 88% of the total capacity in the asset-level database for planned assets despite renewable energy and nuclear plans announced by the electricity authority. The planned assets are primarily represented by coal, followed by gas and oil-fired power plants. An example is the proposed 4 GW Phulbari coal-fired power plant in Rangpur, which complements the proposed coal mine in the same region (Islam and Shafeenul, 2015). Although Bangladesh's position is amongst the countries with the highest climate-incompatible generation, a reconciliation of their energy mixes toward clean and reliable power at the lowest cost would be necessary.

3.2. ECI scenarios with higher asset certainty

The ECI uses FF power generation assets and their remaining generation to estimate whether or not they are climate compatible. However, the index encompasses assets under-construction or planning stages, which can be pending agreement, awaiting bids, or under predevelopment feasibility or further approvals. This means that these assets bring uncertainty to the index and, therefore, could deviate results since these investments can be withdrawn, cancelled, abandoned, or delayed. Therefore, this section presents scenarios without considering planned assets and how abandoning or considering abatement for power generation assets would affect countries' performance towards climate-compatible generation – see Fig. 4.

The results show the impact of new plant investments (e.g., under construction or planned) on aligning with a decarbonised power sector. We have identified the following patterns; (i) 143 out of 170 are set to meet carbon neutrality if they abate or reconsider their under-construction and planned assets, and (ii) the number goes lower for countries committing to their under-construction assets

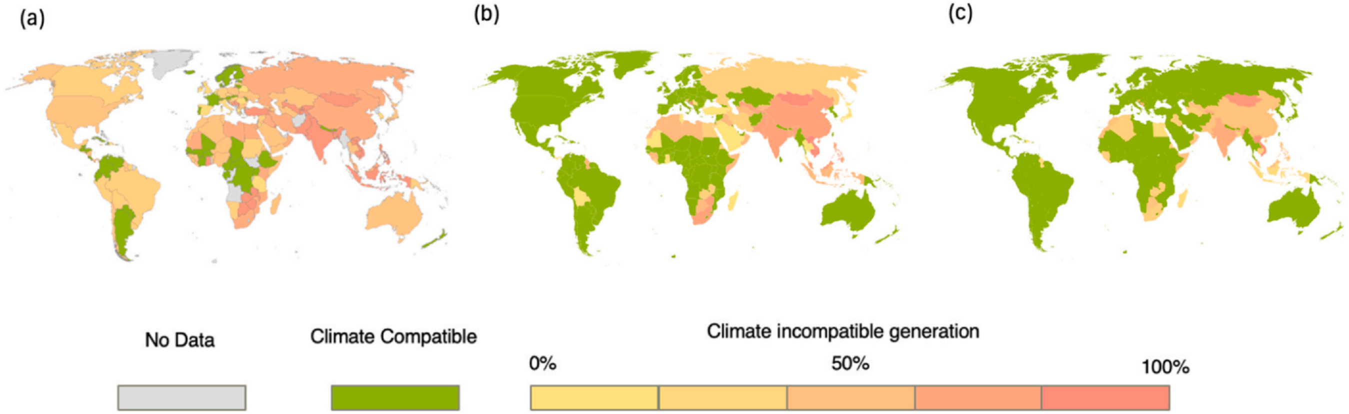


Fig. 4. (a) The ECI (b) a map showing ECI for committed FF power generation assets (i.e., operating and under construction plants only). (c) a map showing ECI for current FF power generation assets (i.e., operating plants only).

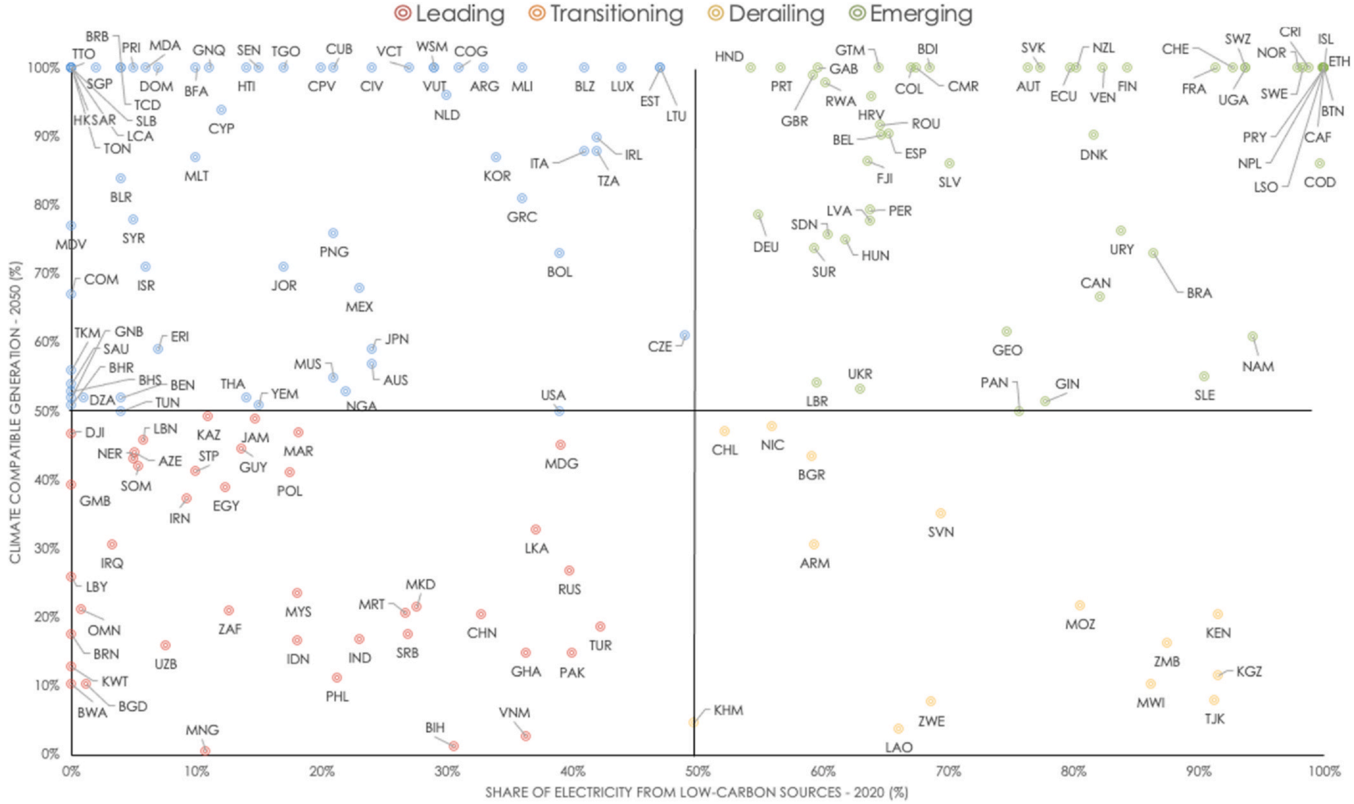


Fig. 5. A classification of various countries highlighting the share of low-carbon electricity in 2020 versus climate-compatible generation in 2050 to illustrate the patterns of transition and which countries are leading, transitioning, derailing, or emerging. The country-level electricity mixes were retrieved from (IEA, 2020).

and halting planned plant investments to 89 countries out of 170, (iii) lastly, only 30 out of 170 countries are expected to become climate-compatible by committing to their stated assets scenario (incl. operating, under construction and planned).

3.3. Analysis of transition patters

The results from ECI and the underlying analysis revealed several patterns which have been categorised into various archetypes to assess countries' positioning within the index and how it changes over time. These are classified as follows: (i) Leading, (ii) Transitioning, (iii) Derailing, and (iv) Emerging.

Leading

In this archetype, countries dependent on baseload low carbon generation using hydro, geothermal, biomass or nuclear generally perform favourably. This includes countries such as Sweden, Norway, Iceland, Switzerland, Paraguay etc. – see 6. This dependency on renewable or nuclear baseload generation assets meant that investments in unabated conventional generation (if any) were minimal and targeted toward operating models for peak or load following. These countries are typically endowed with abundant dispatchable renewable or nuclear resources, however, changing policies or resource availabilities can alter progress toward fully climate compatible generation. For example, Germany's phase-out of nuclear assets led to inevitable investments in baseload coal-fired assets to mitigate the intermittent local generation of solar and wind, together with elevated interconnector imports. Thus, in this model, Germany could miss its allowable budget for FF resources by 20% to align with carbon neutrality by 2050.

The index also shows that countries with relatively low electricity access and power generation e.g., Lesotho, Central African Republic, and Ethiopia are performing relatively superior in the index considering their low dependency on unabated FF power while leapfrogging to decentralised renewables. These countries are positioned to examine the least cost pathways for electrification which could be through solar home systems or other micro-grid applications. However, it is reasonable to argue that the priority should be tailored towards increasing electrification rates rapidly using any least-cost energy sources. However, these countries can generally tailor their investments toward climate-aligned energy sources.

Transitioning

Countries with the potentially highest pace of transition are generally placed in this archetype. They start from a relatively modest low carbon resource and gradually elevate aligning FF generation toward climate compatibility. The analysis shows that smaller countries (e.g., islands) are likely to become more agile in progressing and adapting their unabated FF generation toward carbon neutral levels while diversifying their electricity base.

Those counties ranked moderately are those with diversified energy sources, typically have a mixture of baseload comprising of coal, gas, hydro or nuclear combined with solar and wind generation. The theme of those countries typically comes into two categories: those who are transitioning to renewables and are getting more diversified e.g., Czech, Ireland, Bolivia etc. These countries in most cases are likely to meet their climate targets from the existing portfolio, but their investment decisions will have an impact on whether or not they are subject to having a climate-incompatible generation. Although the US, for example, is set to reach domestic net zero emissions a decade earlier than the global average according to the IEA (IEA, 2021). However, this might likely require a longer time horizon as the US is expected to have roughly 50% of its FF generation incompatible with its carbon budget.

Moreover, countries in the Middle East e.g., Saudi Arabia, have an increasing amount of unmet climate-compatible FF generation. These are largely correlated with the FF reserve abundance, resulting in reinforcing loops to leverage existing resources. Middle eastern countries are also endowed with renewable energy sources such as solar, and to a lesser extent, wind. Many countries are attempting to alleviate domestic oil-power generation for exports and integrate more renewable generation, particularly of the fact that intermittency is easier to deal with during early penetrations.

Derailing

Countries with a renewable-dominant production but do not manage to maintain the investment levels of unabated FF assets within climate compatible levels are generally placed in this category. Many of these countries attempt to expedite their electrification efforts by allocating capital toward centralised unabated conventional sources (e.g., Zambia, Kenya or Laos). These continued investments arise when hydro resources start to become depleted and requirements for dispatchable centralised generation become more pressed despite efforts in developing micro-grids and solar home systems.

Emerging

Here, we have identified countries making insufficient progress toward climate-compatible generation. The general characteristic of those countries (e.g., Mongolia, Vietnam, Indonesia etc.) depend heavily on highly-pollutant base load fuels to meet their growing demand e.g., coal and oil. The main motive for this is the lack of alternative resources and proper policies tailored towards incentivising a diversified portfolio of generation.

Moreover, emerging economies such as China and India are investing heavily in conventional as well as renewable generation. However, since these countries have tremendous population and GDP growth, they are constantly investing in capacity to ensure the base load is being met despite growing electricity demand and heightened electrification. The business-as-usual for these countries denotes climate targets are unlikely to be met since the majority of the investments are coal-fired assets. China, for example, has a weighted-average conventional assets age of 26 years, with 117 GW of conventional assets under construction and another 322 GW planned for implementation. Compared with 93 GW of low carbon/abated resources under construction and 153 GW planned, this means existing as well as future investments are not completely optimised toward climate compatibility.

Although ECI provides an indicative insight into various types of countries and their progress towards carbon neutrality, it is important to match those indices with in-depth country-level analysis to understand the characteristics and recent trends to validate and justify the index positioning.

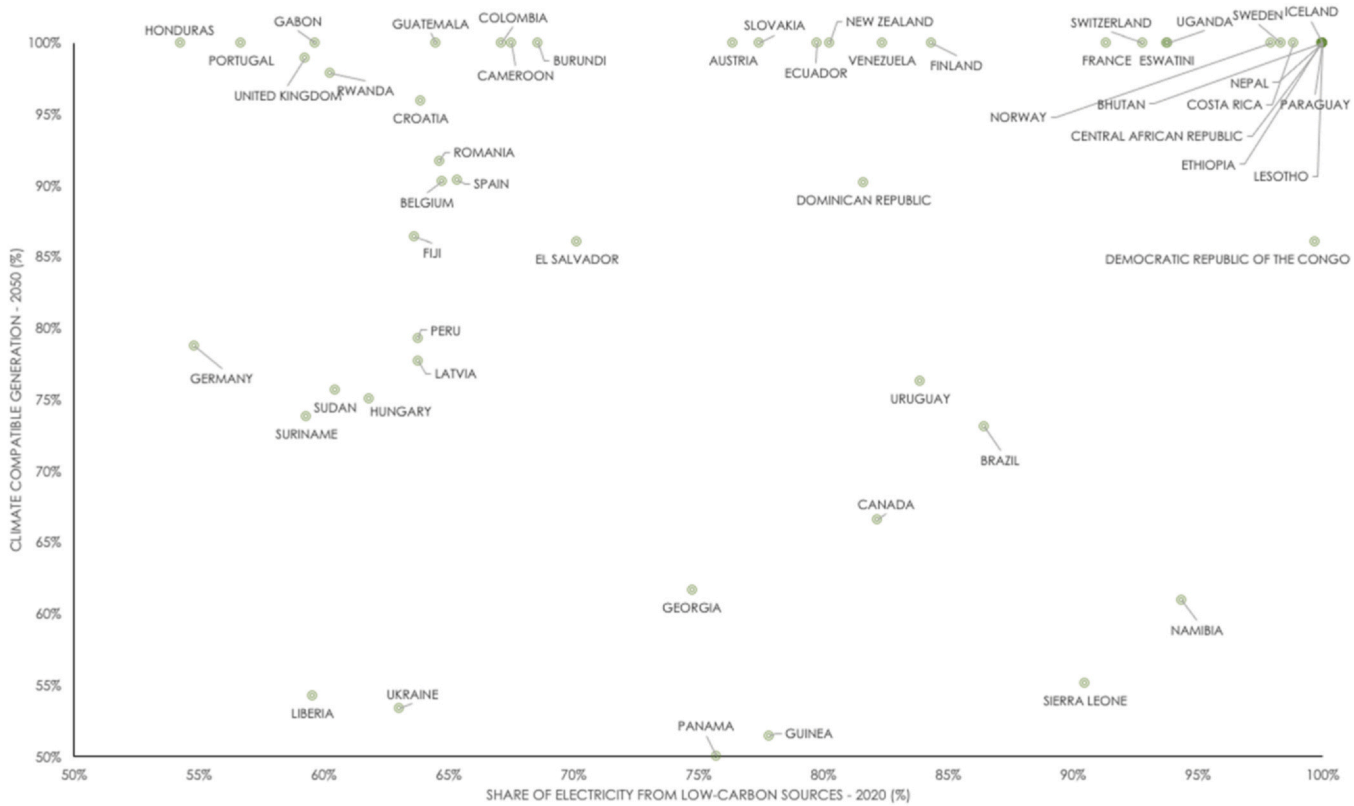


Fig. 6. The share of low-carbon electricity in 2020 versus climate-compatible generation in 2050 for leading countries.

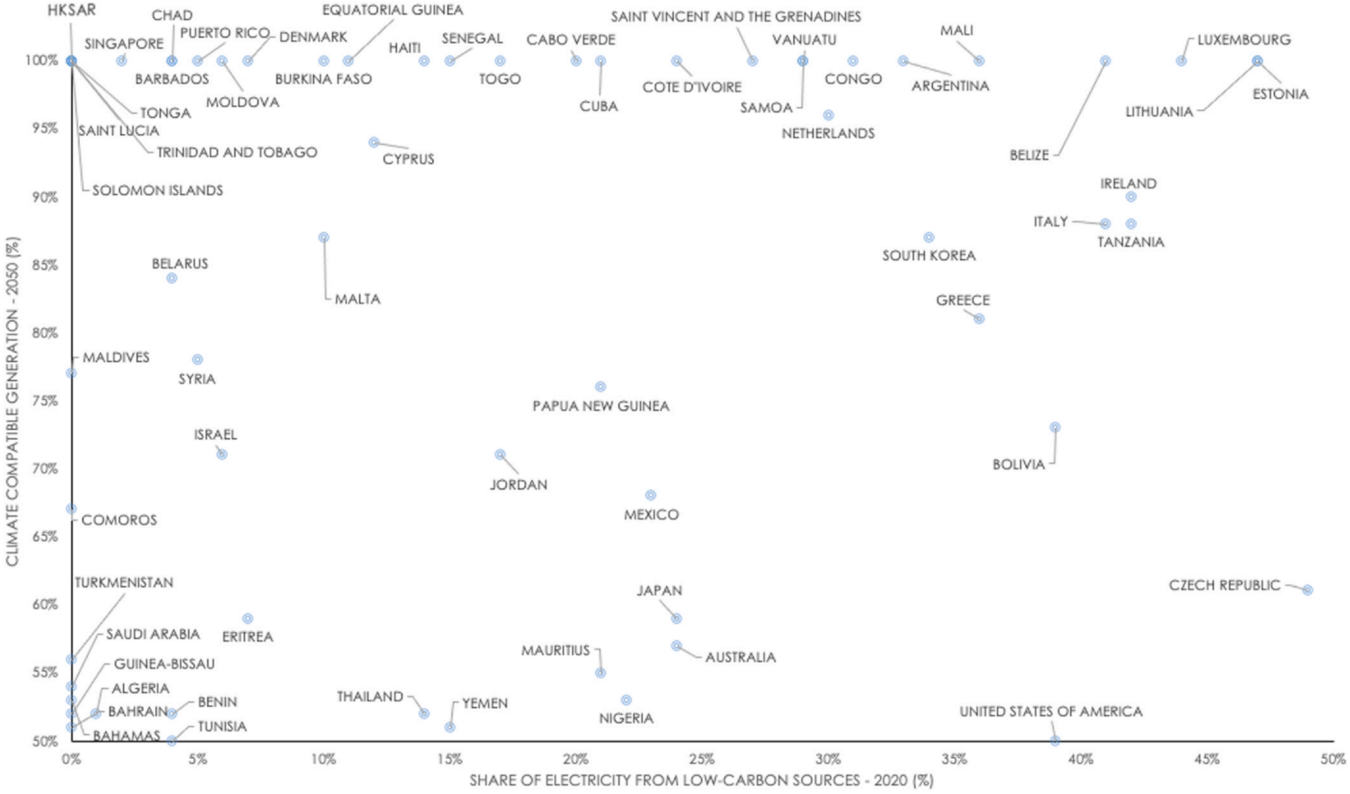


Fig. 7. The share of low-carbon electricity in 2020 versus climate-compatible generation in 2050 for transitioning countries.

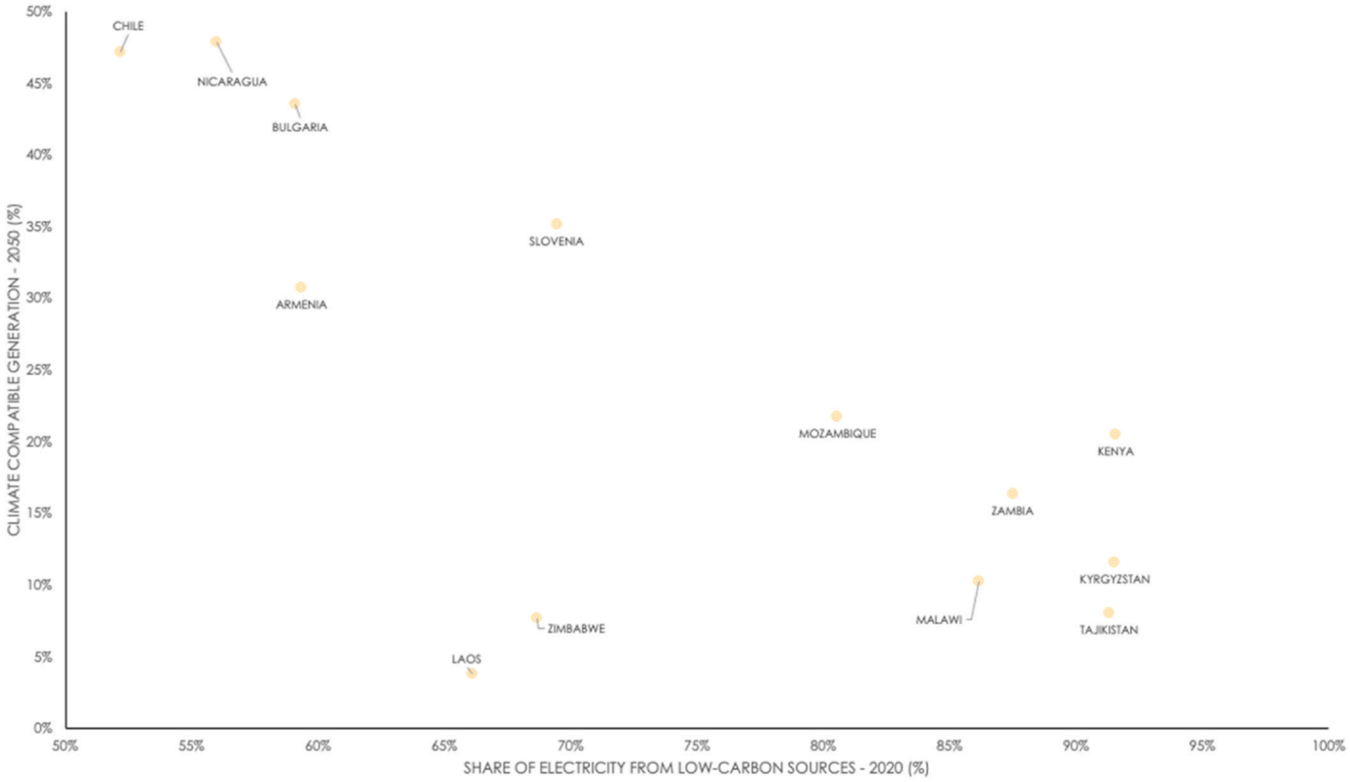


Fig. 8. The share of low-carbon electricity in 2020 versus climate-compatible generation in 2050 for derailing countries.

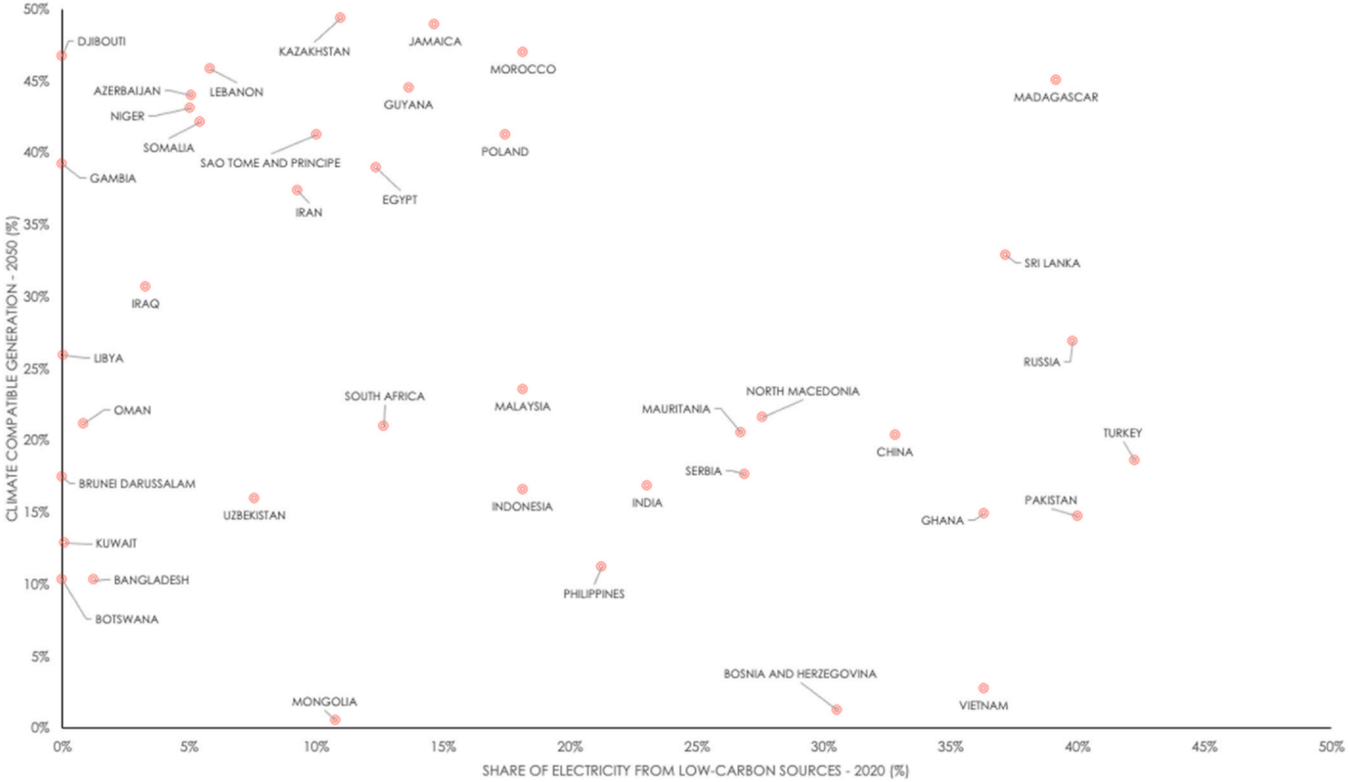


Fig. 9. The share of low-carbon electricity in 2020 versus climate-compatible generation in 2050 for emerging countries.

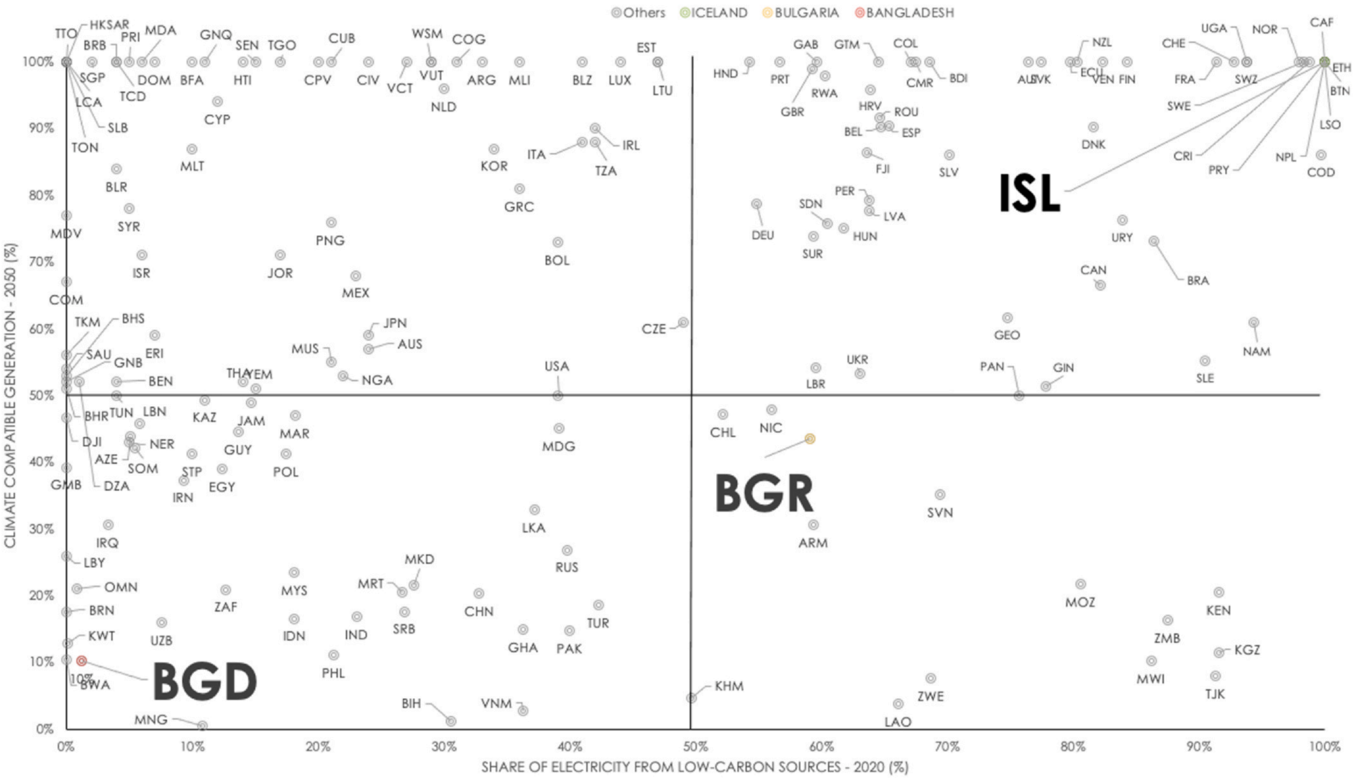


Fig. 10. Iceland, Bulgaria and Bangladesh's positioning within the index and related archetypes.

Case Studies

In order to develop an understanding of how different countries are positioned in various percentiles, a separate case study was conducted for three countries in three different percentiles (top, middle and bottom) to assess the underlying reasons that led these countries to be classified accordingly.

Firstly, from the leading countries archetype, Iceland, which is not only expected to meet the net-zero by 2050 target but is already becoming climate compatible. In Iceland, approximately 99.98% of electricity production in 2020 came predominantly from hydro (70%) and geothermal (30%), which has been meeting a growing demand from 7958 GWh in 2002–17,680 in 2019 according to Statistics Iceland (Statistics Iceland, 2019). For future investments, Iceland is gearing towards utilising onshore and offshore wind generation assets due to its potential (with average wind speeds around 18 m/s), with a pilot project of 1.8 MW installed back in 2013 (Ragnarsson et al., 2015). The intermittency will be mitigated by pre-existing baseload hydro and geothermal resources. Therefore, Iceland is classified as climate compatible in ECI for a carbon-neutral generation mix.

Secondly, among derailing countries, Bulgaria was classified with moderate climate incompatibility. The country is ranked 102 out of 170 for the fraction of climate-incompatible generation. Bulgaria has a diversified electricity generation base where hydro represents roughly 11% of its generated electricity, coal 38%, nuclear 34%, natural gas 6%, solar 3%, wind power 3%, and biomass accounts for 4% (Rodríguez-Monroy et al., 2018). Around half of the FF assets were constructed before the 2000 s and the fleet is of moderate age structure. The country is keep investing in unabated conventional generation with 1.5 GW coming online by 2025 compared with 1.3 GW for solar and wind. The number of unabated FF power plants, together with the inherent long life of these assets has shifted Bulgaria's position slightly toward a more moderate ranking.

Thirdly, Bangladesh, the country with one of the highest climate-incompatible generation is selected from the emerging countries' archetype. Bangladesh was ranked 168 of 170 countries. The electricity sector in Bangladesh is booming in recent years and growing at 5% per year on average in electricity generated which led to almost 100% electricity access in 2022 (Amin et al., 2022). The growth was primely driven by gas and oil-fired power plants which represent together with coal almost 99% of the energy generated in 2019 (Das et al., 2020). These recent installations led to a relatively young FF fleet with a total installed capacity of 20 GW as of 2019 (Das et al., 2020). For planned assets, FFs account for 88% of total capacity in the asset-level database despite renewable energy and nuclear plans announced by the electricity authority. The planned assets are represented largely by coal, followed by gas and oil-fired power plants, which indicates that not only continued investment in unabated FFs are present, but more drastically pollutant and longer-lasting coal. An example of such is the proposed 4 GW Phulbari coal-fired power plant in Rangpur which complements the proposed coal mine in the same region (Islam and Shafeenul, 2015). Although Bangladesh's position is amongst the countries with the highest climate-incompatible generation, a reconsideration of their energy mixes toward clean and reliable power at the lowest cost can be met with climate-compatible generation – whether abated FFs or renewable.

These case studies complement the index findings by highlighting existing transition patterns within these countries and assigning their classification based on the combination of operating, under construction and planned assets. The index helps to determine whether these countries are heading towards climate-compatible infrastructure; whether it is abated FFs or low-carbon technologies to ensure a climate-aligned future.

4. Conclusions

We develop a novel electricity climate-compatibility index (ECI) to be used as a single metric to assess countries' progress towards decarbonised power generation. We identified that using a single metric to assess climate-compatibility is useful to form an initial understanding of where different countries stand in relation to the energy transition. Precisely, we estimate the climate-compatible/incompatible generation based on past and existing decisions made on power generation asset investments.

The ECI also showed that climate-compatibility for many countries could be achieved by rethinking their under-construction and planned asset investments, whether through abatement measures or cleaner alternatives. For example, this study identified that 89 out of 170 countries could become climate compatible (compared to 30 out of 170 in the ECI) in their electricity sector simply by rethinking their investment strategies for planned assets. This is especially true for highly polluting assets with a considerable technical lifetime.

Furthermore, the study backs the results with examples to develop an understanding of how different countries are positioned in various percentiles. We found that the main reason these countries are classified to their corresponding percentiles is primarily based on their asset average weighted age and the percentage of their future FF power generation assets relative to installed capacity.

This paper presents a comprehensive analysis, culminating in the development of a novel Electricity Climate-Compatibility Index (ECI). The ECI emerges as a ground-breaking tool designed to measure and evaluate the progress of various countries towards achieving net-zero-aligned fossil fuel (FF) generation by the year 2050. The genesis of this tool is rooted in an extensive review of existing literature, where the concept of climate compatibility was meticulously examined and defined. By employing the ECI, this study offers a singular metric to gauge climate compatibility, a critical aspect in understanding each country's position in the energy transition, particularly in a world increasingly constrained by climatic considerations.

The utility of the ECI in this context is further enhanced when juxtaposed with results from existing literature and related works, underscoring its effectiveness in providing an initial, yet comprehensive, assessment of different countries' standings in the transition towards environmentally sustainable energy sources. This leads to several pivotal policy recommendations, each anchored in the insights gleaned from the ECI's application.

Firstly, there is an urgent call for early action. Given the accelerating pace and expanding scale of the transition, coupled with the growing immediacy of climate threats, investors, policymakers, and utility companies are advised to incorporate climate-compatibility criteria into their investment decisions. This approach should extend beyond mere emissions considerations to encompass alignment with national and international net-zero objectives, thereby minimizing potential exposure to carbon taxes and other climate-related constraints. Investments should be analyzed not just on an individual source basis but, more crucially, on a portfolio basis, to optimize for complementary energy sources.

The second recommendation emphasizes the need for shorter payback periods for investments in unabated FF power generation assets. Suggesting a range of 15–25 years, this strategy is aimed at reducing the risk of exposure to climate-incompatible generation. Moreover, shorter payback periods would confer greater operational flexibility to FF assets, allowing them to transition from baseload to load-following or peak-shaving power plants post investment recovery.

Thirdly, the paper advocates for strategies to reduce domestic FF consumption, particularly for export purposes. This involves reevaluating the continued operation of high-pollutant, inefficient, and underutilized FF generating assets, and instead redirecting fuel consumption towards more liquid exports, such as crude oil and liquified natural gas.

Another key recommendation is the early integration of intermittent renewables into the energy mix. As more FF generating assets reach the end of their operational lifespan, replacing retired capacity with renewable energy investments becomes increasingly viable. This strategy is particularly effective during initial phases when the grid can better accommodate higher levels of intermittent generation due to the presence of sufficient dispatchable generation capacity.

The paper also underscores the importance of addressing highly pollutant plants. It argues that the core issue lies not with FFs per se but primarily with emissions. Consequently, the early retirement of highly polluting and inefficient assets is posited as a significant step towards substantial carbon emission reduction. A holistic approach to managing generation asset portfolios is essential in identifying these assets for further consideration.

For assets currently under construction, the paper suggests incorporating abatement measures, noting that Carbon Capture and Storage (CCS) retrofits are notably costlier for operational assets due to their exclusion from the initial design phase. Adjustments and reviews for the feasibility of CCS/U during the construction phase could offer a means to mitigate the risk of climate incompatibility.

The seventh recommendation deals with alternative investment strategies and abatement measures for planned assets. The study reveals that the inclusion of planned assets significantly reduces the number of climate-compliant countries, thereby endangering net-zero targets. A reassessment of these investments or the implementation of abatement measures on an asset-level basis is recommended. This approach should be complemented by multiple scenario analyses to ensure overall contribution towards climate compatibility.

Lastly, the paper calls for the development of national carbon-neutral targets and pathways. Utilizing various downscaled country-level Integrated Assessment Models (IAMs), the study provides estimates and projections for net-zero targets and generation scenarios. However, the optimal approach for each country is to design and develop its own net-zero pathway, taking into account specific national factors such as pace, scale, and characteristics to ensure a clean, secure, and cost-effective energy supply.

For future work, the findings derived from the index will support and guide discussions on both national and cluster levels, enabling an in-depth analysis of each country's asset base. This analysis will inform and guide future investor and policy decisions towards achieving climate compatibility. Investigating the asset base of each country may reveal several insights, including possibilities for retrofits, supply reductions, fuel switching, reinvestment in clean technologies, or reallocating domestic consumption for exports. It would also be beneficial to encompass all sources of emissions, not just the power sector, to determine each country's progress towards holistic decarbonization.

Although the ECI effectively indicates countries at an amplified risk of climate incompatibility, it is important to note that the index is time-sensitive and only includes power plant data up to 2020. Market changes, investment patterns, and policy interventions all contribute to variations in climate compliance for these economies. Furthermore, the index does not account for abated FF assets. It is anticipated that countries with significant FF generating assets will adopt Comprehensive Carbon Emission (CCE) methods to ensure that all emissions are reduced, reused, recycled, or removed. In such scenarios, evaluating abated FF assets and their implications on the ECI would be constructive. This evaluation is expected to reduce overall emissions while maintaining and fully leveraging existing FF assets.

For future work, the findings derived from the ECI will support and guide future discussions on a national or cluster level to conduct an in-depth analysis of the asset base for each country to guide and inform future investor and policy decisions for climate-compatibility. By investigating the asset base for each country, several insights could emerge, including retrofits, supply reductions, fuel switching, re-investment in clean technologies or freeing domestic consumption for exports. It would also be desirable to encompass all sources of emissions and not only the power sector to determine countries' progress towards holistic decarbonisation. The power sector emissions account for only a portion of the issue, and other challenges exist in transport and heat, for example.

Although the ECI indicates countries with amplified risk of climate-incompatibility, the index is time-sensitive and only captures power plant data up to 2020. Market changes, investment patterns and policy interventions could drastically alter the country's climate-alignment. Moreover, the index does not account for abated FF power generation assets. Countries with significant FF power-generating assets are likely to adopt circular carbon economy (CCE) methods to ensure all emissions are reduced, reused, recycled, or removed. In such a scenario, it would be constructive to evaluate abated FF power generation assets and their implications on the ECI, which is expected to reduce the overall emissions while continuing to operate FF power generation assets.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.ject.2024.04.005.

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