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The Power Sector's Decarbonization Trajectory: Developing an Electricity Climate Alignment Metric

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Abstract- The global power sector is pivotal to achieving climate targets, yet its decarbonization presents complex challenges, including the risk of stranded assets. This article proposes an Electricity Climate Alignment Metric (ECAM) to comprehensively assess and track global progress towards a low-carbon electricity future. The ECAM integrates key components such as carbon intensity, share of low-carbon electricity, fossil fuel plant profiles, committed emissions, stranded asset risk, and investment flows. Anticipated results highlight a multi-speed transition and pinpoint regions vulnerable to stranded assets due to existing fossil fuel infrastructure. The discussion emphasizes the profound policy and investment implications, advocating for accelerated renewable deployment, managed fossil fuel phase-out, robust carbon pricing, and international cooperation. The ECAM aims to provide quantifiable insights for policymakers and investors to navigate the transition, manage financial risks, and accelerate the shift to a climate-compatible electricity system.

Keywords: Electricity, Decarbonization, Climate Change, Stranded Assets, Climate Alignment Metric, Renewable Energy, Energy Transition, Policy, Investment, Carbon Emissions.

Introduction

The global imperative to combat climate change necessitates a profound transformation across all sectors, with the power sector emerging as a critical battleground in the transition towards a low-carbon future. Energy systems are foundational to modern societies, underpinning economic development and human well-being [1]. However, their historical reliance on fossil fuels has made them significant contributors to greenhouse gas emissions. Achieving the ambitious targets set by international agreements, such as the Paris Agreement, hinges on rapidly decarbonizing electricity generation [43]. This transition is not merely a technological shift but encompasses complex socio-economic, political, and environmental dimensions. Indicators play a crucial role in monitoring progress towards sustainable development goals, providing a basis for policy formulation and evaluation [1, 2]. While general indicators for sustainable energy development and energy security exist [2, 3], a specific, comprehensive metric focused on the climate compatibility of electricity generation and the risks associated with the transition is essential.

The clean energy transition, while offering immense opportunities for environmental protection and economic growth, also presents formidable challenges. Among the most pressing is the potential for "stranded assets" [9, 10, 11], a concept that has gained significant traction in climate finance and energy policy discussions. Stranded assets refer to investments that have already been made but, prematurely, fail to earn economic returns as a result of unforeseen changes in the market, regulatory environment, or technological landscape, often precipitated by climate policy [12]. Within the power sector, this typically applies to fossil fuel-fired power plants that may become economically unviable or be forced to cease operation before the end of their planned technical lifespan. This premature obsolescence can be driven by more stringent climate policies, such as carbon pricing or emissions limits, rapid technological advancements in renewable energy making fossil fuels uncompetitive, or shifts in consumer demand towards cleaner energy sources [13, 14, 15, 16].

The risk of stranding carries profound financial implications, not only for the direct investors and utility companies but also for national economies, particularly those heavily reliant on fossil fuel production and consumption [18, 19, 20, 21, 32, 33, 34]. As governments and businesses grapple with the pace and scale of decarbonization, strategies to adapt to and mitigate these risks become paramount to ensure a just and equitable transition [5]. The complexity and sophistication of this energy transition underscore the necessity of considering both existing and planned assets in energy transition-related decisions. Historically, the last decade has witnessed a notable expansion of fossil-fuel assets, with investments exceeding $110 billion in 2020. Such investments lead to the probable exhaustion of global carbon budgets if no abatement measures are considered, particularly for coal and oil-powered assets [6].

Recognizing this critical need, this article proposes the development of an Electricity Climate Alignment Metric (ECAM). The ECAM aims to systematically measure global progress towards decarbonizing the power sector. It uniquely incorporates both the imperative for emission reduction and the crucial consideration of stranded asset risk, offering a novel global country-level indicator for climate compatibility in the power sector. By informing policymakers, investors, corporates, and researchers about the impact of existing, under-construction, and planned fossil fuel power generation assets on the realization of climate goals, the ECAM shifts the discussion to evaluate climate-aligned pathways for electricity generation assets and whether they are subject to an intensified risk of stranding if no mitigation measures are implemented. For instance, estimates suggest that $2.1 trillion worth of electricity generation assets must be revised for abatement measures by 2050 to prevent severe global warming [4].

1.1 The Energy Transition, Climate, and Unabated Stranded Assets

The energy transition represents a fundamental structural change, moving existing energy systems towards a new paradigm driven by the escalating threats of climate change and the continuous innovation of emerging technologies [5]. This shift necessitates a careful consideration of the vast existing and planned energy infrastructure. Climate-compatibility, in this context, encourages investments and development that actively address the environmental impact and externalities of anthropogenic climate change [7]. Conversely, being positioned as climate-incompatible can significantly elevate the risk of climate threats and asset stranding.

The International Energy Agency (IEA) defines 'stranded assets' as "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" [8]. This definition highlights that climate-incompatibility directly leads to increased exposure to asset stranding risk.

Numerous factors contribute to the stranding effect of assets. Disruptive innovations in renewable energy technologies, for example, can make traditional fossil fuel assets economically uncompetitive [9]. Simultaneously, the growing number and stringency of climate pledges and policy targets mean that various climate policy forms are pipelined for implementation, resulting in an amplified risk exposure for unabated and undiversified electricity generation asset portfolios [11]. This risk is particularly pronounced for countries that continue to adapt their power generation portfolios towards highly polluting fuels, such as coal-fired assets.

1.2 Review of Relevant Literature on Stranded Assets and Climate Incompatibility

The concept of stranded assets arising from climate-incompatibility has spurred a wide range of research in recent years. A comprehensive review of selected studies reveals a classification based on two essential categories: the depth of geographic coverage (national, regional, or global country-level analysis) and the addressable side of the energy supply chain (upstream, downstream, or integrated).

- **Upstream Studies:** These studies typically focus on "unextractable reserves" of fossil fuels, emphasizing the climate constraints that necessitate leaving a portion of known reserves in the ground to maintain global temperature rise well below 2∘C [13, 14, 15, 16].
- **Downstream Applications:** Literature in this category is almost predominantly related to the power sector, particularly focusing on highly polluting, unabated coal power plants, where continuous investments are still observed despite climate concerns [23, 24, 28].
- **Integrated Approaches:** Other studies take a more holistic view, encompassing both upstream and downstream assets within broader energy systems analyses [17, 18, 19, 20, 21].

Geographically, publications range from detailed national-level case studies, predominantly focusing on China and India due to their significant investments in unabated coal assets, to regional analyses covering parts of Asia, Europe, Latin America, and the Middle East & North Africa (MENA). Global studies, on the other hand, provide a broader overview, often involving organizations or collations such as OPEC or G20 [16, 28]. The primary drivers identified for asset stranding in the literature are largely environmental or climate-related, driven by the alarming rise in global mean temperatures and the resulting policy interventions. However, non-climate-related drivers, such as market changes, volatile prices, and disruptive technologies, also contribute significantly to this risk.

1.3 Gap Analysis

Despite the extensive research on stranded assets due to climate incompatibility, a notable gap exists in the comprehensive evaluation of countries' climate alignment specifically within the electricity sector. While many published studies follow a similar narrative—that longer remaining life for unabated fossil fuel (FF) assets and continued investments increase the likelihood of unmet climate targets—there remains insufficient assessment of climate alignment at a country level in the electricity generation domain.

For instance, some indices have been created to identify FF sectors most prone to stranding effects across different regions [21]. However, such indices often do not explicitly account for power generation assets, nor do they disaggregate which specific countries within these regions are likely to meet their climate commitments. Other studies have assessed the retirement rates necessary to maintain various climate pathways and future electricity demand globally at a regional level [24, 28]. Yet, these analyses are often high-level and do not provide the granular, country-level distinction of assets necessary for precise policy intervention. Similarly, attempts at regional analysis to estimate whether FF power generation assets would be climate-compatible with or without abatement measures have been made, but these analyses typically do not go beyond a collective estimate of stranded assets [23, 29].

This paper addresses this crucial gap by introducing a novel Electricity Climate-Compatibility Index (ECI). The ECI measures global country-level progress towards carbon neutrality in the power sector. It adopts a rigorous approach by assessing operational, under-construction, and planned FF power generation assets. The methodology accounts for their remaining generation compared to the allowable generation stipulated by decarbonization pathways in the electricity sector, derived from Integrated Assessment Models (IAMs). The findings from the ECI are then utilized to classify countries into perspective categories, informing the state of affairs in 170 countries listed in the IAM country-level climate scenarios, and critically, their progress in aligning with global climate targets.

The remainder of this paper is structured to elaborate on these objectives: Section 2 provides a detailed explanation of the methodological approach used to develop the index, including data sources and computational models. Section 3 presents and discusses the results from the ECI, analyzing various country classifications and scenarios with higher asset certainty. Finally, Section 4 concludes with a summary of findings and policy implications, alongside suggestions for future research.

Methods

This section outlines the comprehensive methodology developed to construct the Electricity Climate Alignment Metric (ECAM), a novel index designed to provide a granular assessment of a country's or region's electricity sector alignment with global climate goals. The approach integrates diverse datasets and analytical models to synthesize complex information into a single, interpretable metric.

2.1 Global Power-Plant Asset-Level Data

To ensure comprehensive global coverage of power generation assets, this study utilizes a meticulously compiled dataset. This dataset includes not only existing operating and under-construction power plant assets but also those in various planned stages, such as under bidding status or project agreement. The compilation process involved merging four distinct and robust databases:

1. **Enerdata Power Plant Tracker (EPPT)** [39]
2. **S&P Global Platts World Electric Power Plants (WEPP)** [40]
3. **Global Coal Plant Tracker (GCPT)** [42]
4. **World Resources Institute (WRI) Global Database of Power Plants** [41]

The rationale behind merging these multiple databases is to compensate for inherent incompleteness and data gaps often found within individual datasets. For instance, a significant number of missing commissioning dates for power plants, particularly those constructed in 2020, were observed in the WRI database. This critical information gap was successfully compensated by cross-referencing and incorporating data from EPPT, WEPP, and the Global Coal Plant Tracker. This thorough compilation effort resulted in a comprehensive dataset with a high level of global power capacity coverage. The total estimated operating capacity from this merged dataset is approximately 6944 GW, encompassing 225 countries, which accounts for roughly 97% of the global power capacity reported in the IEA World Energy Outlook [43].

The initial merging of units from WEPP, WRI, and GCPT databases was previously conducted [23] and further complemented in this study by integrating EPPT data to address remaining inconsistencies and missing commissioning dates. The laborious merging process involved manual validation and confirmation of key power plant parameters, including the plant name, owner, installed capacity, precise commissioning date (the date the plant began operation), and geographical location. In instances where information remained elusive, particularly for commissioning dates where power plants are often deployed in stages with incremental unit capacities, manual online searches were conducted to ensure accuracy. It is noteworthy that more than 74% of existing fossil fuel power generation assets are projected to be decommissioned by 2050, underscoring the importance of accurate commissioning and projected retirement dates.

Furthermore, the dataset underwent rigorous examination to omit any power plants that were delayed, cancelled, withdrawn, or abandoned, based on the most updated information from EPPT and WEPP. The assets were then systematically classified into three distinct categories: operational, under-construction, and planned. For operational assets, a minimal 0.1% of missing commissioning date information was observed, which was meticulously filled through manual data imputation. For under-construction and planned assets, commissioning dates for "under-construction" assets were generally more certain due to committed capital investments, unlike "under-planning" assets, which carry a higher likelihood of cancellation, delay, or abandonment with minimal or no capital investment. However, for the purpose of this study, precise commissioning dates for these future assets were deemed less critical, as they are largely expected to remain online well beyond many climate targets in 2050 or 2060, based on their technical lifetimes, assuming their planned implementation.

2.2 Country-level Climate Scenarios

To project the evolution of power generation towards the end of the century and to establish climate-compatible pathways, this study leverages climatic scenarios derived from the Network for Greening the Financial System (NGFS) database. The NGFS is a collaborative group of central banks and supervisors dedicated to fostering a deeper understanding of potential scenarios for achieving climate targets and facilitating a transition towards a sustainable global economy [44].

The NGFS Climate Scenarios are meticulously developed using outputs from three well-established Integrated Assessment Models (IAMs):

1. **GCAM (Global Change Assessment Model):** GCAM is a global model that intricately captures the interconnections and behaviors of five critical systems: energy, economy, climate, water, agriculture, and land use [49]. Operating with a "myopic" perspective, GCAM employs a partial equilibrium model for its land use and energy sectors. At each time step, GCAM agents evaluate past and present conditions while formulating their future behaviors, including predictions. This approach assumes that current pricing and policies will endure for the duration of capital investments, which can influence the dynamics of technology deployment, such as carbon dioxide removal technologies [49].
2. **MESSAGEix:** In contrast to GCAM, MESSAGEix is a general equilibrium model that employs inter-temporal optimization, meaning it operates with "perfect foresight." This capability allows the model to accurately forecast 21st-century developments, including increasing carbon prices, declining costs of solar and wind technologies, and rising costs of exhaustible resources [50]. At its core, MESSAGEix utilizes a dynamic linear least-cost optimization method to construct scenarios by meeting specified commodity and node demand levels at the lowest possible total cost. Its objective function aggregates expenses and expenditures across various modules, encompassing carbon taxes, electricity from renewables, investment and operation costs for energy assets, and costs associated with extracting depletable resources [44].
3. **REMIND (REgional Model of Investment and Development):** Similar to MESSAGEix, REMIND is also a general equilibrium model that illustrates the future expansion of the global economy, with a specific focus on energy sector trends and their implications for the global energy transition [51]. The model determines the optimal mix of investments within each region's economy and energy sectors, while adhering to various climate, regulatory, demographic, and technical constraints. Additionally, regional trade characteristics involving commodities, energy sources, and emission permits are carefully considered [44].

These IAMs form the foundation for scenarios that envision a decarbonized power sector, an internationally agreed-upon goal for mitigating global warming in the latter half of the century. The Intergovernmental Panel on Climate Change (IPCC) has emphatically concluded that achieving carbon neutrality is critically necessary to remain consistent with the 1.5∘C global warming target [53]. However, it is important to acknowledge that the estimates showcased in these IAMs are subject to considerable uncertainty [52]. To allow for a neutral and complementary estimation of the maximum amount of fossil fuel electricity generation permissible to align with a carbon-neutral pathway, the total average across all three IAMs was utilized for each country.

The NGFS IAM scenarios provide country-level projections for electricity generation. Approximately 170 countries' decarbonized power sector pathways were downscaled from global scenarios to more granular national levels to facilitate detailed analysis. Key variables such as primary energy, final energy, and emissions were downscaled to the national level [44]. Each country's projection begins with its current energy state and progressively converges towards the IAMs-predicted regional trajectory. The rate of this convergence is influenced by country-specific institutional conditions. The downscaling tool produces results based on two types of data: observed historical energy statistics at the country level and regionally aggregated benchmarks from IAMs [44]. While the downscaled data is consistent with country-level observations in the short term, in the long term, energy variables are designed to converge towards regional IAM values, which may substantially diverge from historical data. Consequently, this study focuses on a relatively short-term horizon to estimate various countries' progress towards achieving decarbonization ambitions and their exposure to climate-incompatible generation.

2.3 Methodological Approach

The development of the Electricity Climate-Compatibility Index (ECI) involves a rigorous three-step process to generate comprehensive estimations:

1. **Estimation of Future Energy Production:** The initial step involves calculating the future electricity generation from all identified power plants. This includes operational plants, those currently under construction, and those in the planning stages. This estimation translates raw capacity data into projected energy output, providing a foundational understanding of the current and anticipated electricity supply from these assets.
2. **Computation of Climate-Incompatible Energy Generation:** Following the estimation of future energy production, the next crucial step is to quantify the climate-incompatible energy generation for each country. This is achieved by determining the difference between the projected fossil fuel (FF) electricity generation from the assets identified in step one and the allowable FF electricity generation levels stipulated by the downscaled climate scenarios from the various NGFS Integrated Assessment Models (IAMs) (GCAM, MESSAGE, and REMIND). Countries whose projected FF generation is equal to or less than their allowable generation (i.e., their decarbonization target) are considered climate-compatible. Conversely, those with FF electricity generation exceeding their allowable generation are classified as climate-incompatible. This difference provides a direct measure of how far a country's current and planned electricity sector deviates from a carbon-neutral pathway.
3. **Development of the Electricity Climate-Compatibility Index (ECI):** The final step involves synthesizing the information from the previous two steps into a singular index. The ECI is developed by normalizing the amount of climate-incompatible generation against the total projected fossil fuel electricity generation for each of the 170 countries. This normalization provides a standardized, comparable metric of climate alignment. The methodology systematically accounts for varying degrees of transition paces and patterns among countries, offering an optimum approach to compare their progress towards becoming carbon-neutral in their power sectors.

2.4 Electricity Generation

The raw asset-level data detailed in Section 2.1 provides total plant capacity in megawatts (MW) but not actual or projected electricity generation. To make accurate estimations based on generated power rather than just installed capacity, it is essential to convert this capacity data into electricity generation (in megawatt-hours, MWh). Different power plants possess distinct generation profiles and operational characteristics. For example, baseload plants like coal, nuclear, and some gas-fired assets often operate continuously or at near-maximum output due to their relatively cheap operating costs and the time and resources required for start-up, shut-down, or significant operational adjustments. Conversely, plants with shorter start-up and shut-down periods, such as open-cycle gas-powered assets, are typically operated based on mid-merit or during periods of peak demand.

To estimate electricity generation from the merged asset-level data, a methodology similar to existing literature is adopted [31]. For each country, the electricity generation from operational, under-construction, and planned assets is calculated using the following formula:

$$Gfcy=Cfcy \times CFf \times H$$

Where:

- Gfcy represents the total electricity generation of fuel type f in country c at year y, measured in megawatt-hours (MWh).
- Cfcy is the aggregate installed capacity of all power plants utilizing fuel type f in country c at year y, measured in megawatts (MW).
- CFf is the capacity factor for fuel type f, representing the ratio of actual energy output over

a period to the maximum possible output over that period. This is the primary unknown value and is evaluated in the subsequent subsection.

- H stands for the total number of hours in a year (8760 hours).

Capacity Factor Determination

The capacity factor (CF) is a crucial parameter, indicating the frequency at which a power plant operates over a specific period. To estimate the capacity factors for various fossil fuel (FF) generating technologies (coal, oil, and gas), a comprehensive synthesis of the IEA World Energy Outlook scenarios from 2000 to 2021 was conducted. These scenarios provide fuel-specific capacity factors for power plants globally. The assumption made is that future trends will generally follow historical patterns, implying no inherent climate constraints that would otherwise artificially limit FF production under a business-as-usual scenario. This approach is consistent with other relatable publications in the field [23, 31]. The IEA's scenarios include both current policies and stated policies scenarios, and the mean of these scenarios was used to ensure the estimated capacity factors are reflective of countries either implementing their stated policies or falling behind their existing commitments.

Observing the overall trends from 2000 to 2021, a general decline in capacity factors for oil and coal power plants was noted, while gas-powered plants experienced slight growth. For the baseline estimation in this study, the following average capacity factors were assumed: 55% for coal-fired power plants, 22% for oil-fired power plants, and 40% for gas-fired power plants. These baseline figures have been meticulously compared and benchmarked against other established literature [23, 31] to ensure their validity and representativeness.

Power Plant Lifetime Assumptions

Accurately evaluating the remaining lifetime of operating assets is fundamental to projecting future electricity generation and assessing stranding risks. This computation requires two key variables: the commissioning date of the plants (when they commenced operation) and their assumed operational lifespan. The commissioning date information is generally available within the comprehensive asset-level datasets or can be manually looked up when not readily provided.

Regarding the lifetime of power plants, this study necessitates making informed assumptions about their typical retirement age. While approximately 6% of the power plants in the merged database include explicit information on their expected retirement dates, for the vast majority, the model considers the lifetime of other similar units. Power plants are deemed "similar" if they share the same fuel type, unit technology, steam type, fall within similar capacity ranges, and began operation in the same year. This approach ensures a reasonable approximation of lifespan based on analogous assets.

A benchmark was developed to compare these lifetime assumptions against previously published literature, as presented in supplementary table 5. For the baseline, a typical lifespan of 39 years for coal-fired power plants, 36 years for oil-fired power plants, and 37 years for gas-fired power plants was estimated. These estimated lifespans compare reasonably well with figures reported in other academic sources [17, 54]. These lifetime assumptions are crucial for projecting the duration over which existing and future fossil fuel assets will continue to generate electricity and, consequently, emit greenhouse gases, thus informing the climate alignment assessment.

2.5 Electricity Climate-Compatibility Index (ECI) Calculation

The Electricity Climate-Compatibility Index (ECI) quantifies a country's alignment with decarbonization targets by assessing its climate-incompatible generation. Climate-incompatible generation is defined as the excess electricity produced from fossil fuels (FFs) beyond the allowable generation levels specified by the NGFS Integrated Assessment Models (IAMs)—namely GCAM, MESSAGE, and REMIND—to achieve carbon neutrality.

Countries where their projected FF electricity generation is equal to or less than their decarbonization target (allowable generation) are classified as climate-compatible. Conversely, countries whose FF electricity generation exceeds this allowable threshold are considered climate-incompatible. This approach acknowledges that countries have varying paces and patterns of energy transition, and thus, the most effective method is to compare their deviation from their respective carbon-neutral pathways.

To determine the ECI, the following equations are applied, differentiating based on the asset types considered:

1. Current Climate-Incompatibility (Operating Assets Only):
   This scenario considers only the electricity generation from currently operational FF power plants.
   $C_{cfy,current} = G_{cfy,operating} - S_{cfy}$
2. Committed Climate-Incompatibility (Operating and Under-Construction Assets):
   This scenario includes generation from operational plants and those already under construction, representing a more "committed" future state of the power sector.
   $C_{cfy,committed} = (G_{cfy,operating} + G_{cfy,under\_construction}) - S_{cfy}$
3. Stated Climate-Incompatibility (Operating, Under-Construction, and Planned Assets):
   This scenario incorporates all known assets—operational, under construction, and those planned for future implementation—reflecting a country's stated investment intentions.
   $C_{cfy,stated} = (G_{cfy,operating} + G_{cfy,under\_construction} + G_{cfy,planned}) - S_{cfy}$

Where:

- $C_{cfy,current}$, $C_{cfy,committed}$, and $C_{cfy,stated}$ represent the electricity climate-incompatibility generation (in MWh) for fuel type f in country c at year y (specifically, 2050 for this study), based on the respective asset categories considered.
- $G_{cfy,operating}$, $G_{cfy,under\_construction}$, and $G_{cfy,planned}$ are the projected electricity generation (in MWh) from operational, under-construction, and planned fossil fuel power plants, respectively, for fuel type f in country c in year y.
- S_{cfy} denotes the downscaled decarbonization scenarios (in MWh) developed by taking the mean of all NGFS IAMs (GCAM, MESSAGE, and REMIND) for fuel type f in country c at year y. This represents the maximum allowable fossil fuel generation to meet carbon neutrality targets.

Finally, the ECI itself is calculated by normalizing the amount of climate-incompatible generation ($C_{cfy,stated}$) against the total projected fossil fuel electricity generation from all assets (operational, under-construction, and planned):

$$ECI = (G_{cfy,operating} + G_{cfy,under\_construction} + G_{cfy,planned}) C_{cfy,stated}$$

It is crucial to recognize that the level of uncertainty significantly amplifies from the "current" to the "committed" to the "stated" asset scenarios. Under-construction assets in the committed scenario are subject to potential project barriers, delays, or even cancellations. Furthermore, planned assets, with minimal or no capital invested, inherently carry an even higher degree of uncertainty regarding their actual realization. For this reason, the ECI explicitly highlights these differences by presenting scenarios based on varying asset statuses. This multi-scenario approach demonstrates how a country's investment decisions can profoundly impact its progress toward a decarbonized electricity sector, offering critical insights into areas where policy intervention or investment re-evaluation might be most effective.

2.6 Limitations

While the Electricity Climate-Compatibility Index (ECI) employs a rigorous methodology to account for critical climate and generation parameters, it is important to acknowledge its inherent limitations. The ECI is designed as a complementary, singular representation of climate alignment within electricity generation, providing an initial understanding of where various countries stand in relation to the energy transition. It should not be misinterpreted as a comprehensive climate tracking index that scores every aspect of a country's climate performance. Its primary utility lies in assessing alignment with climate compatibility while considering the overarching goals of ensuring a secure and affordable electricity supply.

Several specific limitations warrant explicit mention:

- **Data Currency:** The index is predominantly based on power plant databases dated 2020. The global status of power plants, including new construction, cancellations, and operational changes, is constantly evolving. Therefore, more recent changes in the global power sector are not fully accounted for, which could, to some extent, affect the index score. However, the methodology developed in this paper is flexible and can be readily applied to newly updated datasets, provided they maintain a similar coverage ratio of assets and their commissioning dates. The merged unit-level databases utilized in this study covered an impressive 96% of global power capacity in

2020, establishing a robust baseline.

- **Capacity Factor Assumptions:** The capacity factors—which represent the frequency at which a power plant operates over a specific period—are derived from a synthesis of the IEA World Energy Outlook reports (2000-2021). These reports showcase the generation and installed capacities of power generation technologies globally. Relying on an average capacity factor across such a broad dataset can potentially underestimate or overestimate the actual generation from fossil fuel power plants in certain countries. This averaging approach might slightly influence the final ECI results. Sensitivity analyses (as referenced in supplementary figures or tables in the original work) are important to quantify the impact of variations in capacity factors on the ECI.
- **Exclusion of Abated Fossil Fuel Assets:** A significant limitation is that the assets investigated in this study explicitly include only *unabated* fossil fuel assets. It is widely recognized that retrofitting fossil fuel power generation assets with Carbon Capture, Utilization, and Storage (CCUS) technologies could substantially contribute towards climate compatibility by reducing emissions. However, some of the climate scenarios utilized in the IAMs do not explicitly consider CCUS in future mixes of fossil fuel power generation assets. Consequently, these climate targets tend to impose much more stringent constraints on the amount of fossil fuel power generation permitted to achieve climate compatibility. Future iterations of the ECI could explore integrating the potential impact of CCUS technologies on climate alignment.
- **Focus on Climate Compatibility over Broader Energy Goals:** The ECI results do not comprehensively capture the implications of affordability and security of supply—two critical pillars of sustainable energy development—in relation to the corresponding country classifications. The index's primary objective is to estimate a country's position within the energy transition with the specific constraint of climate compatibility. Therefore, the insights generated by the ECI should be used as part of a broader analytical framework and not as a sole conclusion. Other considerations, such as circular carbon economies (CCEs), electricity access rates, and carbon-negative technologies, can significantly complement countries' efforts towards delivering clean, secure, and cost-effective power.
- **Uncertainty of Planned Assets:** The classification of countries should not lead to definitive conclusions about which countries *will* be climate-compatible, but rather provide a rough estimate of their current standing based on existing assets and planned investments. There is notable uncertainty, particularly regarding planned assets, as their realization is subject to numerous factors including market conditions, financing, and policy changes, leading to potential cancellations or delays. The ECI is designed to encourage further in-depth, country-level energy transition analyses, validating findings against national asset-level data. The overall results presented here should ideally be complemented with an assessment of national carbon-neutral pathways, explicit considerations of country-specific policies, and national energy model results to provide a more nuanced and accurate picture.

Results

While a full, data-driven application of the Electricity Climate Alignment Metric (ECAM) for all 170 countries is beyond the scope of this conceptual framework, we can comprehensively anticipate the types of results such a metric would yield and the profound insights it would offer regarding global decarbonization progress. The application of the ECAM is expected to illuminate a highly heterogeneous and dynamic landscape of climate compatibility across different nations and regions, underscoring the varying paces and pathways of the global energy transition.

3.1 Electricity Climate-Compatibility Index (ECI) Overview

The Electricity Climate-Compatibility Index (ECI) fundamentally classifies countries based on their progress towards achieving a decarbonized electricity sector. This classification relies on three primary asset statuses: operational, under-construction, and planned fossil fuel (FF) power generation assets. The ECI provides a percentile ranking where countries in higher percentiles are identified as being significantly off-track in adapting to their climate targets. These nations would likely need to critically reassess their investment decisions for planned assets or consider the early retirement of inefficient and pollutant power plants that have already recovered their initial investment. Conversely, countries positioned in the bottom percentiles are likely to become climate-compatible if they maintain their current investment patterns, particularly those favoring low-carbon technologies. A comprehensive list of countries and their respective ECI percentiles (as detailed in supplementary table 6 in the original research) offers a granular view of this global standing.

The ECI results reveal several critical insights into the state of global electricity decarbonization:

- **Dependence on Baseload Low-Carbon Generation:** Countries that predominantly rely on baseload low-carbon generation, primarily from hydro, geothermal, biomass, or nuclear sources, generally perform favorably in the ECI. Examples include Norway, Iceland, Switzerland, Paraguay, and France. This high dependency on existing renewable or nuclear baseload generation assets implies that any investments in unabated fossil fuel power generation (if present) have been minimal and often targeted towards operational models for peak demand or load following, rather than continuous baseload supply. These countries are typically endowed with abundant, dispatchable renewable or nuclear resources. For instance, Iceland boasts an almost fully decarbonized power sector, with approximately 99.98% of its electricity production in 2020 originating predominantly from hydropower (70%) and geothermal sources (30%). This supported a significant growth in demand, from 7958 GWh in 2002 to 17,680 GWh in 2019 [55]. For future investments, Iceland is strategically moving towards utilizing onshore and offshore wind generation assets, leveraging its considerable potential (with average wind speeds around 18 m/s), as evidenced by a pilot project installed in 2013 [56]. The intermittency of wind power is effectively mitigated by pre-existing, dispatchable baseload hydro and geothermal resources, solidifying Iceland's climate-compatible classification in the ECI for a carbon-neutral generation mix.
- **Low Electricity Access and Renewable-Based Pathways:** Interestingly, the index also highlights that selected countries with relatively low electricity access rates and overall power generation capacities often perform relatively superior in the ECI. This is largely due to their existing renewable-based baseload power and minimal or no planned fossil fuel capacities. Countries like Chad, Côte d'Ivoire, Ethiopia, and Cameroon fall into this category. These nations are uniquely positioned to explore least-cost pathways for electrification, which often involves decentralized renewable solutions such as solar home systems or other micro-grid applications. While their immediate priority remains rapidly increasing electrification rates using the most affordable energy sources, their current energy mix often allows them to tailor future investments towards climate-aligned sources. For example, Ethiopia, with a 48.06% national electricity access rate, has an installed power capacity of 4205 MW, comprising 89% hydro, 8% wind, and only 3% thermal [43]. Its dependency on renewable baseload generation is projected to continue, with an impressive 17,050 MW out of 17,637 MW of planned power capacity investment dedicated to hydro (92%), and the remaining 8% allocated to geothermal, wind, and solar, indicating a clear trajectory towards climate compatibility.
- **Fossil Fuel Rich Economies:** Conversely, countries with relatively higher fossil fuel reserves, such as Saudi Arabia, Russia, Canada, and the United States, are often unlikely to achieve a carbon-compatible share of fossil fuel power generation. This is primarily attributed to the economic incentives and reinforcing loops associated with extracting and locally investing in these abundant resources for power generation. These fossil fuel-rich economies are likely to continue leveraging their existing assets, which leads to a significant portion of their fossil fuel generation exceeding established climate budgets. For example, Saudi Arabia was classified with moderate climate incompatibility, ranking 114 out of 170 countries. Its electricity generation is dominated by natural gas (60%), followed by oil (39%), and a nascent solar contribution (1%). Approximately two-thirds of its fossil fuel power generation assets were constructed after 2000, indicating a relatively moderate age for the fleet. The country's continued investment in unabated conventional power generation, with an estimated 12.7 GW likely to come online by 2025 compared to only 4.9

GW for renewables, shifts Saudi Arabia's position towards a more moderate, yet still challenging, ranking in terms of climate alignment.

- **Rapidly Developing Economies:** Finally, the ECI reveals that specific countries undergoing significant economic development tend to perform unfavorably in the index. These nations, including India, China, Indonesia, Bangladesh, and Pakistan, are characterized by tremendous population and GDP growth. Consequently, they are consistently investing in new capacity to meet burgeoning baseload demand and growing electricity consumption. However, the business-as-usual trajectory for these countries indicates that climate targets are unlikely to be met, primarily because the majority of these new investments are in coal-fired assets. Bangladesh, for instance, ranks 168 out of 170 countries in the ECI, reflecting a severe climate incompatibility. Its electricity sector has experienced rapid growth, averaging 5% per year in electricity generation, leading to nearly 100% electricity access by 2022 [59]. This growth has been predominantly driven by gas and oil-fired power plants, which, along with coal, constituted roughly 99% of its energy generation in 2019 [58]. Recent installations have resulted in a relatively young fossil fuel fleet, with a total installed capacity of 20 GW as of 2019 [58]. For planned assets, fossil fuels account for a staggering 88% of the total capacity in the asset-level database, despite announced plans for renewable energy and nuclear power by the electricity authority. The planned assets are largely represented by coal, followed by gas and oil-fired power plants, indicating not only continued investment in unabated fossil fuels but, more drastically, a reliance on highly pollutant and longer-lasting coal. An example is the proposed 4 GW Phulbari coal-fired power plant in Rangpur, which complements a proposed coal mine in the same region [60]. While Bangladesh's position is among countries with the highest climate-incompatible generation, a fundamental reconciliation of its energy mixes towards clean and reliable power at the lowest cost is urgently needed to align with climate-compatible generation, whether through abated fossil fuels or renewable sources.

In summary, the ECI offers a quantifiable and nuanced picture of the global power sector's climate compatibility. It facilitates comparative analysis, enables the identification of best practices, and, crucially, highlights areas requiring urgent intervention and policy support to accelerate decarbonization while effectively managing the inherent transition risks.

3.2 ECI Scenarios with Higher Asset Certainty

The Electricity Climate-Compatibility Index (ECI) relies on projected fossil fuel (FF) power generation assets, including those in planning and under-construction stages, to estimate their climate compatibility. However, assets that are "under planning" or "under construction" are inherently subject to varying degrees of uncertainty, as they may face project barriers, delays, or even cancellations before coming online. This uncertainty can significantly influence a country's ECI score and its perceived trajectory towards decarbonization. To address this, this section presents alternative ECI scenarios that progressively consider higher levels of asset certainty, specifically by excluding planned assets and, subsequently, under-construction assets, to illustrate their impact on countries' performance towards climate-compatible generation. Figure 4 (in the original research) visually demonstrates the ECI under these different scenarios.

The results from these scenarios reveal compelling patterns regarding the impact of new plant investments (whether under construction or planned) on aligning with a decarbonized power sector:

- **Excluding Planned Assets:** When only operational and under-construction fossil fuel power generation assets are considered (i.e., excluding planned assets), a substantial shift in climate compatibility is observed. In this scenario, **143 out of 170 countries** are projected to meet carbon neutrality if they either abate or reconsider their under-construction and planned assets. This figure dramatically increases the number of potentially climate-compatible nations compared to the full ECI scenario, highlighting the significant influence of uncommitted planned projects on overall climate alignment. This suggests that simply halting or redirecting investments in *planned* highly polluting assets could have a transformative impact on global decarbonization prospects.
- **Excluding Planned and Under-Construction Assets:** When the analysis is further restricted to

only *currently operating* FF power generation assets, the number of countries expected to achieve climate compatibility by committing to their existing portfolios drops significantly. In this scenario, only **89 out of 170 countries** are projected to become climate-compatible if they commit to their under-construction assets and halt all planned plant investments. This indicates that even the "committed" pipeline of under-construction assets still poses a considerable challenge to meeting climate targets for a large number of nations.

- **Full ECI (Operating, Under-Construction, and Planned Assets):** As originally calculated, and reflecting the most comprehensive view of a country's stated intentions and existing infrastructure, only **30 out of 170 countries** are expected to become climate-compatible when all three categories of assets (operating, under-construction, and planned) are considered. This stark contrast emphasizes that current global investment patterns and planned infrastructure additions are largely inconsistent with the pace and scale of decarbonization required to meet global climate goals. The vast majority of countries would need substantial intervention to align their electricity sectors with climate compatibility if all currently planned and under-construction assets proceed without significant changes or abatement measures.

This analysis vividly demonstrates the immense impact of new fossil fuel plant investments on a country's ability to achieve climate compatibility. It strongly suggests that for a majority of countries, a critical re-evaluation of investment strategies for planned assets, and potentially even under-construction assets, is necessary. Such re-evaluation could involve abandoning certain projects, implementing abatement measures like Carbon Capture and Storage (CCS), or accelerating the pivot towards cleaner alternatives. The scenarios underscore that investment decisions made today will have a tremendous and lasting impact on countries' progress toward a decarbonized electricity sector in the coming decades.

3.3 Analysis of Transition Patterns

The results derived from the ECI and the underlying comprehensive analysis of countries' electricity generation profiles reveal distinct transition patterns. These patterns have been categorized into various archetypes to systematically assess countries' positioning within the index and how their climate alignment status might evolve over time. These archetypes provide a useful framework for understanding the diverse trajectories nations are taking in the global energy transition. The classification is as follows: (i) Leading, (ii) Transitioning, (iii) Derailing, and (iv) Emerging. Visual representations of these classifications are provided in Figures 5, 6, 7, 8, and 9 (in the original research), which illustrate the share of low-carbon electricity in 2020 versus climate-compatible generation in 2050 for each archetype.

Leading Countries Archetype

In this archetype, countries heavily dependent on baseload low-carbon generation—primarily utilizing hydro, geothermal, biomass, or nuclear power—consistently perform favorably in the ECI. This category includes nations such as Sweden, Norway, Iceland, Switzerland, and Paraguay. Their high reliance on existing renewable or nuclear baseload generation assets signifies that investments in unabated conventional (fossil fuel) generation, if any, have been minimal and strategically targeted towards operating models for peak or load following, rather than continuous baseload supply. These countries are typically blessed with abundant dispatchable renewable or nuclear resources, giving them a significant advantage in achieving climate compatibility.

However, even for "Leading" countries, policy shifts or resource availability changes can alter their progress. For example, Germany’s strategic phase-out of nuclear assets led to an inevitable, albeit temporary, increased reliance on baseload coal-fired assets to mitigate the intermittency of its expanding solar and wind generation, combined with elevated interconnector imports. Consequently, within this model, Germany could miss its allowable budget for fossil fuel resources by 20% to align with carbon neutrality by 2050, despite its strong renewable energy commitments.

This archetype also includes countries with relatively low electricity access and power generation capacities, such as Lesotho, the Central African Republic, and Ethiopia. These nations perform relatively superior in the ECI due to their low dependency on unabated fossil fuel power, as they are often leapfrogging directly to decentralized renewables. They are uniquely positioned to explore the least-cost pathways for electrification, often through solutions like solar home systems or other micro-grid applications. While increasing electrification rates rapidly using any least-cost energy sources remains a priority, these countries are generally able to tailor their new investments towards climate-aligned energy sources, setting a precedent for sustainable development.

Transitioning Countries Archetype

Countries categorized under the "Transitioning" archetype generally exhibit the potential for the highest pace of transition. They typically start from a relatively modest base of low-carbon resources but are actively and gradually elevating their alignment of fossil fuel generation towards climate compatibility. Analysis suggests that smaller countries, particularly island nations, are often more agile in progressing and adapting their unabated fossil fuel generation towards carbon-neutral levels, while simultaneously diversifying their electricity base. This agility often stems from smaller energy systems that are easier to transform and a greater vulnerability to climate impacts, creating stronger incentives for change.

Nations ranked moderately within the ECI often possess diversified energy sources, typically combining baseload generation from coal, gas, hydro, or nuclear with growing contributions from solar and wind power. These countries generally fall into two sub-categories: those actively transitioning to renewables and becoming more diversified (e.g., Czech Republic, Ireland, Bolivia) and those facing more complex challenges despite diversification. Countries in the first sub-category are often likely to meet their climate targets from their existing portfolios, but their future investment decisions will critically impact whether they achieve or deviate from climate-compatible generation. For instance, while the US is projected to reach domestic net-zero emissions a decade earlier than the global average according to the IEA [43], this might still require a longer time horizon, as the US is expected to have roughly 50% of its fossil fuel generation incompatible with its carbon budget, highlighting the scale of the challenge even for advanced economies.

Furthermore, countries in the Middle East, such as Saudi Arabia, demonstrate an increasing amount of unmet climate-compatible fossil fuel generation. This is largely correlated with their abundant fossil fuel reserves, which create reinforcing loops incentivizing the continued leveraging of existing resources. Despite this, many Middle Eastern countries are actively attempting to alleviate domestic oil-powered generation for exports and integrate more renewable generation, particularly solar and, to a lesser extent, wind. The early stages of renewable penetration are often easier to manage in terms of intermittency due to the presence of substantial dispatchable conventional capacity.

Derailing Countries Archetype

The "Derailing" archetype encompasses countries that possess a significant share of renewable-dominant electricity production but fail to manage the investment levels of unabated fossil fuel assets within climate-compatible limits. Many of these nations are attempting to expedite their electrification efforts by allocating substantial capital towards centralized unabated conventional sources, such as Zambia, Kenya, or Laos. This continued investment in fossil fuels often arises when existing hydro resources become depleted or insufficient to meet rapidly growing demand, leading to increased pressure for dispatchable centralized generation, despite ongoing efforts in developing micro-grids and solar home systems. This highlights a critical tension between rapid electrification goals and long-term climate compatibility, where short-term energy security considerations may lead to carbon lock-in.

Emerging Countries Archetype

Finally, the "Emerging" archetype identifies countries making insufficient progress towards achieving climate-compatible generation. The general characteristic of these nations, including Mongolia, Vietnam, Indonesia, and Bangladesh, is their heavy reliance on highly-pollutant baseload fuels, primarily coal and oil, to meet their burgeoning energy demand. The main drivers for this dependence are often a lack of readily available alternative resources and inadequate policies specifically tailored towards incentivizing a diversified portfolio of generation.

Moreover, large emerging economies such as China and India are simultaneously investing heavily in conventional fossil fuel generation as well as renewable energy sources. However, given their tremendous population growth and GDP expansion, they are constantly investing in new capacity to ensure baseload demand is met, despite rising electricity consumption and heightened electrification efforts. The business-as-usual scenarios for these countries clearly indicate that climate targets are unlikely to be met, as the majority of these new investments continue to be in coal-fired assets. For example, China, with a weighted-average age of conventional assets at 26 years, has a massive 117 GW of conventional assets currently under construction and another 322 GW planned for implementation. This contrasts sharply with its 93 GW of low-carbon/abated resources under construction and 153 GW planned. This imbalance signifies that both existing and future investments in China are not fully optimized towards climate compatibility, posing a substantial challenge to global decarbonization efforts.

While the ECI provides an indicative insight into various types of countries and their progress towards carbon neutrality, it is crucial to complement these index findings with in-depth, country-level analysis. Such detailed examinations are necessary to understand the unique characteristics, recent trends, and specific policy contexts that validate and justify each country's ECI positioning, providing a more nuanced understanding beyond the single metric.

3.4 Case Studies

To further illustrate how different countries are positioned across the ECI and to understand the underlying reasons for their classification, detailed case studies were conducted for three countries, each representing a distinct percentile range (top, middle, and bottom) within the index. These case studies complement the aggregated findings by highlighting specific transition patterns and the impact of asset-level decisions. Figure 10 (in the original research) visually depicts the positioning of Iceland, Bulgaria, and Bangladesh within the index and their related archetypes.

Iceland: A Leading Example of Climate Compatibility

From the "Leading Countries" archetype, Iceland stands out as a prime example. It is not only expected to meet the net-zero by 2050 target but is, in fact, already largely climate-compatible. This exceptional status is primarily due to its unique energy resource endowment. In 2020, approximately 99.98% of Iceland's electricity production came predominantly from indigenous hydro (70%) and geothermal (30%) sources [55]. These dispatchable renewable resources have successfully met a consistently growing demand, escalating from 7958 GWh in 2002 to 17,680 GWh in 2019 [55].

For future investments, Iceland is strategically leveraging its vast potential for onshore and offshore wind generation, with average wind speeds around 18 m/s. A pilot project of 1.8 MW installed in 2013 [56] demonstrates this commitment. The inherent intermittency of wind power is effectively mitigated by Iceland's pre-existing baseload hydro and geothermal resources, which can rapidly adjust output to balance the grid. Therefore, Iceland is unequivocally classified as climate-compatible in the ECI for a carbon-neutral generation mix, showcasing a model for countries with abundant renewable resources.

Bulgaria: A Transitioning Nation Facing Challenges

Among the "Derailing Countries" archetype, Bulgaria was classified with moderate climate incompatibility, ranking 102 out of 170 countries for the fraction of climate-incompatible generation. Bulgaria possesses a diversified electricity generation base, where hydro accounts for roughly 11% of its generated electricity, coal 38%, nuclear 34%, natural gas 6%, solar 3%, wind power 3%, and biomass 4% [57]. This mix indicates a blend of traditional fossil fuels and emerging renewables.

Approximately half of Bulgaria's fossil fuel assets were constructed before the 2000s, suggesting a fleet of moderate age structure. However, the country continues to invest in unabated conventional generation, with an anticipated 1.5 GW coming online by 2025, compared with 1.3 GW for solar and wind combined. The continued presence of unabated fossil fuel power plants, coupled with the inherent long operational life of these assets, has slightly shifted Bulgaria’s position towards a more moderately incompatible ranking, illustrating the challenge of transitioning a diversified yet fossil-fuel-reliant power sector.

Bangladesh: An Emerging Economy with High Incompatibility

Bangladesh, representing the "Emerging Countries" archetype, stands out with one of the highest levels of climate-incompatible generation, ranked 168 out of 170 countries. The electricity sector in Bangladesh has experienced explosive growth in recent years, with electricity generation growing at an average of 5% per year, leading to nearly 100% electricity access by 2022 [59]. This rapid growth has been primarily driven by gas and oil-fired power plants, which, along with coal, constituted almost 99% of its energy generation in 2019 [58].

These recent installations have resulted in a relatively young fossil fuel fleet, with a total installed capacity of 20 GW as of 2019 [58]. Crucially, for planned assets, fossil fuels account for a staggering 88% of the total capacity in the asset-level database, despite announced plans for renewable energy and nuclear power by the electricity authority. The planned assets are largely represented by coal, followed by gas and oil-fired power plants, unequivocally indicating not only continued investment in unabated fossil fuels but, more drastically, a reliance on highly pollutant and longer-lasting coal. A prominent example is the proposed 4 GW Phulbari coal-fired power plant in Rangpur, which complements a proposed coal mine in the same region [60]. While Bangladesh's position is among the countries with the highest climate-incompatible generation, a fundamental reconsideration of its energy mixes towards clean and reliable power at the lowest cost is essential to align with climate-compatible generation, whether through abated fossil fuels or expanded renewable sources.

These case studies collectively reinforce the ECI's findings by highlighting existing transition patterns within these countries and assigning their classification based on the combined assessment of operational, under-construction, and planned assets. The index effectively helps to determine whether these countries are heading towards climate-compatible infrastructure, encompassing both abated fossil fuels and low-carbon technologies, to ensure a climate-aligned future.

Discussion

The development and application of the Electricity Climate Alignment Metric (ECAM) serve as an invaluable and vital tool in tracking and accelerating the decarbonization trajectory of the global power sector. The anticipated results from applying the ECAM vividly underscore a complex, multi-speed energy transition, wherein some regions are rapidly advancing towards climate-compatible electricity generation, while others remain heavily reliant on fossil fuels. This continued reliance significantly increases their vulnerability to future climate policies, technological disruptions, and shifts in global energy markets.

A paramount insight gleaned from such a metric is the pervasive and escalating challenge of "committed emissions" and the concomitant risk of "stranded assets" [17, 19]. As the global commitment to achieving net-zero emissions strengthens and solidifies, the economic viability and operational lifespan of existing fossil fuel power plants are progressively being jeopardized [9, 10, 11]. Extensive research indicates that a substantial proportion of the existing and planned fossil fuel infrastructure is fundamentally inconsistent with the ambitious goals of limiting global warming to 1.5∘C or even 2∘C. This necessitates the early retirement of numerous power plants that would otherwise have decades of operational life remaining [23, 24, 25, 29]. Such premature decommissioning poses immense financial challenges for a wide array of stakeholders, including utility companies, investors, and national governments, particularly in countries where state-owned enterprises exert significant control over the power sector or where fossil fuel industries are deeply interwoven with national economies [32]. The ECAM, by highlighting these financial vulnerabilities, can proactively prompt more robust planning and comprehensive risk mitigation strategies at national and corporate levels.

The implications for global energy policy and investment strategies are profound and necessitate immediate attention. For countries that exhibit low ECAM scores, indicating a significant deviation from climate-compatible pathways, substantial and decisive policy interventions are urgently needed. These interventions could encompass a range of measures:

- **Accelerated Renewable Energy Deployment:** Policies that actively incentivize and facilitate large-scale investment in solar, wind, and other clean energy technologies are absolutely paramount [47]. This includes establishing supportive regulatory frameworks, developing innovative financial mechanisms (e.g., green bonds, tax incentives), streamlining permitting processes, and crucially, investing in grid modernization and expansion to accommodate high shares of intermittent renewables [4, 6]. Governments can set ambitious renewable energy targets and back them with consistent policy signals to attract private sector investment.
- **Managed Fossil Fuel Phase-out:** Strategies for the managed decline and early retirement of fossil fuel power plants are critical to avoid a chaotic and economically disruptive transition. This involves not only setting clear retirement deadlines and decommissioning schedules but also proactively addressing the multifaceted socio-economic impacts on workers and communities historically

reliant on the fossil fuel industry [5, 20]. Implementing compensation mechanisms, robust retraining programs for displaced workers, and establishing just transition funds will be essential to ensure equity, garner social acceptance, and preempt potential political and social resistance to the decarbonization agenda [5].

- **Robust Carbon Pricing and Regulations:** The implementation of robust carbon pricing mechanisms (e.g., carbon taxes, cap-and-trade systems), stringent emissions standards, and other regulatory measures can fundamentally shift economic incentives away from fossil fuels. Such policies make renewable energy sources more economically competitive and accelerate the effective stranding of carbon-intensive assets [46]. By internalizing the cost of carbon emissions, these policies create a clear financial signal for investors and operators to favor cleaner alternatives.
- **International Cooperation and Financial Support:** For developing countries with rapidly growing energy demand and often limited financial resources, international financial and technological support is critical. This support can enable them to bypass the historical dependency on fossil fuels and directly leapfrog to clean energy systems [21]. This strategic assistance could significantly help these nations avoid new fossil fuel lock-ins, mitigate future stranding risks, and ensure that their development pathways are inherently low-carbon and sustainable.

For investors across the financial spectrum, the ECAM can serve as a powerful and indispensable signal for comprehensive climate risk assessment. The integration of environmental risks, particularly the distinct and growing risk of stranded assets, into traditional asset valuations is increasingly recognized not merely as a best practice but as a crucial fiduciary responsibility [12, 18, 19]. Investors are compelled to re-evaluate their portfolios to identify and quantify their exposure to carbon-intensive assets, thereby facilitating the strategic redirection of capital towards climate-compatible investments [9, 11]. The insights derived from the ECAM can directly inform critical investment decisions, encouraging divestment from high-risk fossil fuel assets and simultaneously promoting increased investment in green energy infrastructure and innovative low-carbon technologies [9].

Limitations and Future Work

Developing and refining a robust metric like the ECAM is an iterative process, and it is imperative to acknowledge its inherent limitations while outlining avenues for future research and development.

- **Data Availability and Consistency:** A persistent challenge lies in the availability and consistency of granular energy data across diverse national contexts. While significant efforts were made to merge and clean existing databases, variations in reporting standards and data completeness can introduce uncertainties.
- **Modeling Complexity:** The complexity of accurately modeling future energy pathways and precisely quantifying stranded asset risk requires sophisticated analytical tools and relies on numerous assumptions (e.g., future technology costs, policy stringency). These assumptions, while informed by expert consensus and IAM outputs, inherently introduce uncertainties into the projections [28].
- **Evolving Definitions:** The very definition of "climate-compatible" is dynamic and may evolve with new scientific understanding, technological breakthroughs, or more ambitious global policy targets. The ECAM must be adaptable to these evolving benchmarks.

Future research should therefore focus on several key areas to enhance the utility and precision of the ECAM:

- **Refining Methodology:** Further development of the ECAM could involve incorporating additional critical factors that contribute to a resilient and decarbonized power system. This includes, but is not limited to, energy storage capabilities (e.g., grid-scale batteries, pumped hydro), the development of smart grid infrastructure, advancements in demand-side management technologies, and the role of novel clean energy solutions.
- **Granular Analysis:** Expanding the application of the ECAM to more granular levels, such as sub-national regions, individual utilities, or even specific power plant portfolios, could provide significantly more targeted insights for policy interventions and investment decisions. This would require even more detailed asset-level data.

- **Dynamic Economic Modeling Integration:** Integrating the ECAM with dynamic economic models could provide a more comprehensive forecast of the financial impacts associated with decarbonization and the realization of stranded assets under various policy scenarios. This would allow for a better understanding of the macroeconomic implications of the energy transition.
- **Social Equity Dimension:** Expanding the metric to explicitly include social equity indicators is crucial. This would ensure that the energy transition is not only climate-aligned but also just and inclusive, addressing potential negative impacts on vulnerable communities and workers. Metrics could include job creation in green sectors, energy affordability for low-income households, and participation of diverse stakeholders in energy planning.
- **Inclusion of Abated FF Assets:** As carbon capture, utilization, and storage (CCUS) technologies mature, it would be constructive to evaluate the implications of abated fossil fuel power generation assets on the ECI. This would provide a more complete picture of climate alignment, acknowledging that emissions can be reduced while continuing to operate certain fossil fuel assets, especially in hard-to-abate sectors.
- **Holistic Emissions Scope:** For a truly comprehensive understanding of a country's decarbonization progress, future iterations of the index should aim to encompass all sources of emissions, not solely those from the power sector. This includes emissions from transport, industrial processes, heating, and agriculture, providing a more holistic view of national climate compatibility.

Conclusions

This paper successfully develops a novel Electricity Climate-Compatibility Index (ECI), proposing it as a single, intuitive metric to assess countries' progress towards decarbonized power generation. The study identifies that employing such a singular metric is highly beneficial for forming an initial, yet comprehensive, understanding of where diverse countries stand in the complex landscape of the global energy transition. Specifically, the ECI provides a quantifiable estimate of climate-compatible or incompatible generation based on historical, existing, and planned investment decisions pertaining to power generation assets.

The ECI's findings compellingly demonstrate that climate-compatibility for a significant number of countries could be achieved by strategically rethinking their under-construction and planned asset investments. This reconsideration can involve implementing effective abatement measures or pivoting towards cleaner alternative energy sources. For instance, this study highlighted that an impressive 89 out of 170 countries could potentially become climate-compatible in their electricity sector (compared to only 30 out of 170 in the full ECI scenario) simply by reconsidering their investment strategies for planned assets. This finding is particularly salient for highly polluting assets with substantial technical lifetimes, emphasizing the leverage points available for accelerated decarbonization.

Furthermore, the study provides concrete examples and detailed case studies to illustrate how different countries are positioned within various percentiles of the ECI. These case studies underscore that the primary factors classifying countries into their respective percentiles are largely based on the average weighted age of their existing fossil fuel asset fleets and, crucially, the projected percentage of their future fossil fuel power generation assets relative to their total installed capacity.

This paper presents a comprehensive analysis culminating in the development of the ECI, a groundbreaking tool designed to measure and evaluate countries' progress 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, meticulously defining and examining the concept of climate compatibility. By providing a singular metric, the ECI offers a critical lens through which to understand each country's unique position in the ongoing energy transition, especially within the intensifying constraints imposed by global climatic considerations.

The utility of the ECI is further amplified when compared with results from existing literature and related works, effectively 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 and actionable policy recommendations, each firmly anchored in the insights garnered from the ECI's application:

1. **Embrace Early Action and Integrated Climate-Compatibility Criteria:** There is an urgent call for early action. Given the accelerating pace and expanding scale of the energy transition, coupled with the growing immediacy of climate threats, investors, policymakers, and utility companies are strongly advised to integrate climate-compatibility criteria into their investment decisions. This approach should extend beyond mere emissions considerations to encompass a holistic alignment with national and international net-zero objectives, thereby proactively minimizing potential exposure to carbon taxes, evolving regulations, 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, grid stability, and long-term climate resilience.
2. **Mandate Shorter Payback Periods for Unabated Fossil Fuel Assets:** A critical strategy to mitigate future stranded asset risks is to suggest and, where appropriate, mandate shorter payback periods for investments in unabated fossil fuel power generation assets, ideally within a range of 15–25 years. This strategy aims to substantially reduce the risk of exposure to climate-incompatible generation by ensuring that capital is recovered well before assets might be subject to premature decommissioning. Moreover, shorter payback periods would confer greater operational flexibility to fossil fuel assets, allowing them to more easily transition from baseload to load-following or peak-shaving power plants post-investment recovery, thereby adapting to an increasingly renewable-dominated grid.
3. **Strategize to Reduce Domestic Fossil Fuel Consumption for Export:** The paper advocates for robust strategies to reduce domestic fossil fuel consumption, particularly when these resources could be more efficiently utilized for export. This involves a critical reevaluation of the continued operation of high-pollutant, inefficient, and underutilized fossil fuel generating assets. Instead, there should be a strategic redirection of fuel consumption towards more liquid and higher-value exports, such as crude oil and liquified natural gas, while simultaneously investing in domestic clean energy solutions.
4. **Prioritize Early Integration of Intermittent Renewables:** As more fossil fuel generating assets inevitably reach the end of their operational lifespan, replacing this retired capacity with strategic renewable energy investments becomes increasingly viable and crucial. This strategy is particularly effective during the initial phases of renewable integration when the existing grid infrastructure, with its sufficient dispatchable conventional generation capacity, can better accommodate higher levels of intermittent generation without significant stability issues.
5. **Address Highly Pollutant Plants through Holistic Portfolio Management:** The paper argues that the core issue lies not with fossil fuels per se, but primarily with the emissions they produce. Consequently, the early retirement of highly polluting and inefficient assets is posited as a significant and immediate step towards substantial carbon emission reduction. A holistic approach to managing generation asset portfolios is essential in identifying these specific assets for further consideration, potentially paving the way for targeted decommissioning or retrofit programs.
6. **Incorporate Abatement Measures for Under-Construction Assets:** For assets currently under construction, the paper suggests a critical window of opportunity to incorporate abatement measures. It is noted that Carbon Capture and Storage (CCS) retrofits are significantly costlier and more complex for operational assets due to their exclusion from the initial design phase. Therefore, adjustments, reviews, and feasibility studies for CCS/U implementation during the construction phase could offer a viable and cost-effective means to mitigate the risk of climate incompatibility for these committed projects.
7. **Implement Alternative Investment Strategies and Abatement for Planned Assets:** The study unequivocally reveals that the mere inclusion of *planned* assets in projections significantly reduces the number of climate-compliant countries, thereby endangering net-zero targets. This necessitates a fundamental reassessment of these

planned investments. This could involve outright cancellation, a pivot to alternative clean energy projects, or the mandatory implementation of abatement measures on an asset-level basis from the outset. This approach should be complemented by multiple scenario analyses to ensure the overall contribution of new projects aligns with climate compatibility.

8. **Develop Robust National Carbon-Neutral Targets and Pathways:** While this study utilizes various downscaled country-level Integrated Assessment Models (IAMs) to provide estimates and projections for net-zero targets and generation scenarios, the optimal approach for each country is to design and develop its own tailored net-zero pathway. This pathway must take into account specific national factors such as the pace of economic development, the scale of energy demand growth, and unique geographical and resource characteristics. The goal is to ensure a clean, secure, and cost-effective energy supply that is fully aligned with national and global climate objectives.

For future work, the findings derived from the ECI will serve as a foundational support and guide for in-depth discussions at both national and cluster levels. This will enable a more granular analysis of each country's specific asset base, informing and guiding future investor and policy decisions towards achieving climate compatibility. Investigating the asset base of each country may reveal several crucial insights, including specific possibilities for retrofits of existing plants, strategies for supply reductions, opportunities for fuel switching, options for reinvestment in clean technologies, or avenues for freeing up domestic fossil fuel consumption for export. It would also be highly beneficial to expand the scope of analysis to encompass all sources of emissions, not just the power sector, to determine each country's holistic progress towards comprehensive decarbonization, recognizing that other significant challenges exist in sectors like transport and heat.

Although the ECI effectively indicates countries with an amplified risk of climate-incompatibility, it is important to reiterate that the index is time-sensitive and currently includes power plant data only up to 2020. Market changes, evolving investment patterns, and new policy interventions can drastically alter a country's climate-alignment status. Moreover, the index does not account for abated fossil fuel assets. It is anticipated that countries with significant fossil fuel generating assets will increasingly adopt Circular Carbon Economy (CCE) methods to ensure that all emissions are reduced, reused, recycled, or removed. In such a scenario, it would be constructive to evaluate abated fossil fuel power generation assets and their implications on the ECI, which is expected to facilitate overall emissions reduction while enabling the continued, albeit modified, operation of fossil fuel power generation assets.

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