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Pathways toward zero-carbon electricity required for climate stabilization

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HIGHLIGHTS

- We compile the carbon content of electricity in published IPCC projections.
- All models agree: climate stabilization requires near-zero carbon electricity.
- All considered countries decarbonize electricity under every climate stabilization target.
- This finding is robust to the unavailability of technologies such as nuclear and CCS.
- Electrification (e.g., electric cars) makes sense within a long-term strategy.

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ABSTRACT

This paper provides pathways of the carbon content of electricity extracted from the Intergovernmental Panel on Climate Change's fifth Assessment Report scenarios database. It demonstrates three policy-relevant aspects of the carbon content of electricity that are implicit in most integrated assessment model results but under-discussed in academia and the policy debate. First, climate stabilization at any level from 1.5 °C to 3 °C requires the carbon content of electricity to decrease quickly and become almost carbon-free before the end of the century. As such, the question for policy makers is not whether to decarbonize electricity but when and how to do so. Second, decarbonization of electricity is still possible and required if some of the key zero-carbon technologies—such as nuclear power or carbon capture and storage—turn out to be unavailable. Third, progressive decarbonization of electricity is part of every country's cost-effective means of contributing to climate stabilization. The pathways of the carbon content of electricity reported here can be used to benchmark existing decarbonization targets, such as those set by the European Energy Roadmap or inform new policies in other countries. They can also be used to assess the desirable uptake rates of electric and plug-in hybrid vehicles, electric stoves and heat pumps, industrial electric furnaces, or other electrification technologies.

1. Introduction and literature review

Power generation plays an important role in global warming for at least two reasons. First, it is responsible for a large share of anthropogenic greenhouse gas (GHG) emissions: today's electricity accounts for almost 14 GtCO2/year, about 29% of total annual greenhouse gas emissions. Reducing the carbon content of electricity would thus decrease global GHG emissions significantly. Second, electricity can be used as a substitute for carbon-intensive fossil fuels in many cases. For instance, direct energy consumption for transportation and housing together represent about 30% of total emissions from energy; and industrial energy consumption, mainly used to produce heat or motion, accounts for an additional 19% [1,2]. Technologies such as electric vehicles, heat pumps, electric furnaces, industrial motors and other electric equipment could in part replace fossil-fuel based counterparts in these sectors, reducing indirectly GHG emissions.

An increasingly consensual result from prospective models is that both decarbonization of electricity supply and electrification of the energy system play a decisive role in reaching climate stabilization [3–14]. Indeed, stabilizing climate change to any level (e.g. 1.5, 2, or 3 °C) requires reducing global net emissions to zero [15–18]. Moreover, switching from fossil fuel to low-carbon electricity is one of the few technical options available to drastically reduce GHG emissions in energy-intensive sectors such as industry, transportation and buildings.

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Despite this consensus and its importance to inform the policy debate, we are not aware of any study that publishes pathways of the future carbon content of electricity consistent with climate stabilization. For instance, while decarbonization of the power sector is implicit in all of the above-mentioned studies, none of them explicitly reports the pathways of the carbon content of electricity.

To fill this gap, this study estimates the carbon content of electricity in a set of existing emission-reduction pathways, and makes those estimates available to decision-makers, researchers in other disciplines, and the public. It reports pathways at the global level, and at the country/region level for Brazil, China, the EU, India, Japan, Russia, and the USA. It also considers a variety of assumptions regarding availability of technology and the ambition of long-term climate targets.

These pathways of the carbon content of electricity may be useful to planners and policymakers designing climate mitigation strategies. They provide a reference on the speed at which decarbonization of the power sector could happen to meet a given climate target. They may thus be used to benchmark existing milestones, such as the ones proposed by the European Commission's energy roadmap [19], the Clean Power Plan that was recently under discussion in the US, or Mexico's ambitious GHG targets [20,21]. These trajectories can further inform new plans in other countries or jurisdictions.

Second, such pathways of the carbon content of electricity are useful to assess the long-term desirability of specific electrification technologies. Indeed, without access to pathways of the carbon content of electricity consistent with climate stabilization, existing studies have focused on the impact of electrification on *current* GHG emissions. For instance, electric vehicles have been found to cause more GHG emissions than conventional vehicles if they are charged in places where, or at time of the days when, electricity is mostly produced from coal [22,23,19,24–30]. This finding has been often taken as an argument that electrification is to be avoided [31]. Similar results have been reported on industrial electric furnaces [32], and buildings [33–35].

Yet, to inform energy and industrial policy, the important question might not be what would be the impact of electrification technologies in the year when they are implemented, but rather whether the adoption of such technologies is consistent with a long-term decarbonization strategy [36,16,37].[1] With transparent pathways of the carbon content of electricity, scholars and analyst from any discipline will be able to leverage results from the IAM community to perform an *integrated life cycle analysis* [40,41]. These pathways can also give a basis to evaluate the impact on GHG emissions of technologies or industrial processes that are too specific to be explicitly represented in an IAM. This paper demonstrates this usage by assessing the desirability of electric cars as an emission-reduction measure in six different regions of the world.

The paper proceeds as follow. The methodological approach is detailed in Section 2. Section 3.1 presents and discusses global pathways of the carbon content of electricity in climate-stabilization scenarios, showing that under the most technology-optimistic assumptions, bioenergy combined with carbon capture and storage (BECCS) allows for producing electricity with negative carbon emissions. Section 3.2 reports pathways in scenarios with constrained deployment of either (i) both nuclear and CCS or (ii) renewable power. In both cases, the carbon content of electricity is still projected to decrease to near-zero levels. Section 3.3 shows that this reduction to near-zero levels of emissions in the power sector occurs in every region of the world represented in IAMs. Finally, Section 3.4 develops an example of how these pathways can be used to assess the relevance of promoting electric cars to reduce carbon emissions. Section 4 discusses the findings and concludes. The Appendix A details pathways at the country/region level, for Brazil, China, the EU, India, Japan, Russia, and the US under different scenarios.

2. Methods

This study uses two main datasets. The first one, AMPERE, comprises a set of 68 pathways generated with 12 different integrated assessment models (IAM) for the purpose of a recent comparison study [42].[2] These pathways cover both the local and global level. For further insights on a global level, we analyze the full IPCC AR5 database of 274 scenarios generated with 56 IAMs [45].

IAMs compute pathways of the socio-economic and energy systems under the constraint set by climate targets. IAMs factor in a wide range of parameters, such as long-term demographic evolution, availability of natural resources, and countries' participation to emission-reduction efforts. Technology costs and maximum penetration rates, in particular, are calibrated using a mix of historical uptake rates and assumptions on learning by doing and autonomous technical progress [46,47].

The methods used to derive pathways vary across IAMs [48]. For instance, some models use intertemporal optimization to assess the least-cost investment and operation plan consistent with a climate target. Others start from a target emission pathways, solve recursively for the carbon price that would deliver the emission target at each time step, and derive investment and operation decisions consistent with the resulting carbon price. IAMs are regularly peer-reviewed in comparison exercises [49,50,48,51,52] and occasionally evaluated against historical data [53,47].

In this study, carbon intensity is defined as CO2 emissions (gCO2) per unit of electricity produced (kWh). Electricity production is restricted to secondary energy/electricity, that is, the total electric energy produced by the power sector, excluding that used by the power supply sector itself for transformation, transportation and distribution (including these losses would result in lower carbon intensities). This carbon intensity measure is then constructed by dividing carbon dioxide emissions from electricity generation by total electricity generation per scenario, model, region, and time step.

Two kinds of limitations should be mentioned in interpreting the results of this study: first, the study is restricted to a subset of IAM trajectories, which may introduce biases; and second, IAMs may imperfectly represent barriers to power generation decarbonization.

The first limitation applies because a subset of IAM trajectories is selected based on the results reported in the IPCC's AR5 and the AMPERE database, because the data is publicly available in the required granularity. Comparing the figures in the main text to Fig. 14 in the Appendix A shows that the findings from AMPERE are consistent with the wider IPCC database of decarbonization pathways [45]. Nonetheless, previous studies have documented the risk of selection bias in IAM reviews, as results are not always reported when targets are unachievable [54]. The sample of trajectories considered here may be affected by selection bias, given some models might not report their results with some generation technologies unavailable. For instance, when availability of some technologies is restricted, such as CCS and nuclear, the number of reported paths decreased, when targeting 450 ppm CO2-eq (this effect is mitigated with the looser 550 ppm CO2-eq constraint).[3] This hints at the potential difficulty of reaching a stringent climatic target if the development of BECCS is constrained [55–57].

The second limitation comes from the fact that IAMs might imperfectly account for several barriers to the decarbonization of power

[1] Electrification also comes with associated health benefits in regions that heavily rely on coal for power generation, see Peng et al. [38]. Assessing how changes in the energy system impacts air quality is another recent application of IAMs, see Shi et al. [39].

[2] We chose this study as it is freely available online [43], other recent studies such as EMF27 [44] are of similar scope, use a broader variety of models and assumptions, and reach qualitatively and quantitatively similar results, but are unfortunately currently not publicly available online in the required granularity.

[3] Such evidence should be taken with caution, as participants were not required to run every scenario (scenarios were ranked as required, recommended, or optional). A smaller number of trajectories does not necessarily reflect selection.