Inter-American
Development Bank

IDB WORKING PAPER SERIES Nº IDB-WP-827

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Climate Change and Sustainable Development Sector

August 2017

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August 2017

Cataloging-in-Publication data provided by the
Inter-American Development Bank
Felipe Herrera Library

Pathways toward zero-carbon electricity required for climate stabilization/ Richard Audoly, Adrien Vogt-Schilb, Celine Guivarche and Alexander Pfeiffer.

p. cm. - (IDB Working Paper ; 827)
Includes bibliographic references.
1. Climate change mitigation. 2. Electric power production-Government policy. 3. Carbon dioxide mitigation. 4. Renewable energy sources. I. Audoly, Richard. II. Vogt-Schilb, Adrien. III. Guivarche, Celine. IV. Pfeiffer, Alexander. V. Inter-American Development Bank. Climate Change Division. VI. Series.
IDB-WP-827

http://www.iadb.org

Pathways toward Zero-Carbon Electricity Required for Climate Stabilization

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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 it. 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.

Keywords: climate change mitigation; life cycle assessment; power supply; carbon intensity; renewable energy

JEL: Q01; Q4; Q5

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Highlights

•All models agree: climate stabilization requires near-zero carbon electricity

•All 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

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/yr., about 29% of total annual greenhouse gas emissions. Reducing the carbon content of electricity would thus decrease significantly global GHG emissions. 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% (IEA, 2017a; WRI, 2018). 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 (Bauer et al., 2015; IEA, 2017b, 2014; IPCC, 2014a; Krey et al., 2014; Luderer et al., 2012; McCollum et al., 2014, 2014; Miotti et al., 2016; Pfeiffer et al., 2016; Sachs et al., 2014; Sugiyama, 2012; Williams et al., 2012). Indeed, stabilizing climate change to any level (e.g. 1.5, 2, or 3◦C) requires reducing global net emissions to zero (Collins et al., 2013; Fay et al., 2015; IPCC, 2013; Rogelj et al., 2015).

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 them, none of the above-mentioned studies 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 (European Commission, 2011), the Clean Power Plan that was recently under discussion in the US, or Mexico's ambitious GHG targets (SEMARNAT and INECC, 2016; Veysey et al., 2014). 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 (Doucette and McCulloch, 2011; Graff Zivin et al., 2014; Hawkins et al., 2012a, 2012b; Katrašnik, 2013; Lewis et al., 2014; Orsi et al., 2016; Richardson, 2013; Sioshansi and Denholm, 2009). This finding has been often taken as an argument that electrification is to be avoided (BBC, 2012). Similar results have been reported on industrial electric furnaces (Thomson et al., 2000), and buildings (Gustavsson and Joelsson, 2010; Ramesh et al., 2010; Zabalza Bribián et al., 2009).

Yet to inform energy and industrial policy, the important question might not be what would be the impact of electrification technologies the year when they are implemented, but rather whether the adoption of such technologies is consistent with a long-term decarbonization strategy (Bataille et al., 2016; Fay et al., 2015; Vogt-Schilb and Hallegatte, 2017).[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 what Hertwich et al. (2014) call an *integrated life cycle analysis* (Ke et al., 2017). This 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. To illustrate this, this paper uses the reported pathways of the carbon content of electricity to assess the desirability of electric cars 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, bio-energy combined with carbon capture and storage (CCS) allows for producing electricity with negative carbon emissions. Section 3.2 then reports pathways in scenarios where

[1] Electrification also comes with associated health benefits in regions that heavily rely on coal for power generation, see Peng et al. (2018). Assessing how changes in the energy system impacts air quality is another recent application of IAMs, see Shi et al. (2017).

deployment of either (i) both nuclear and CCS or (ii) renewable power is constrained. 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 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 (Riahi et al., 2015).[2] These pathways cover both the local and global level. For further insights on a global level, the full IPCC AR5 database of 274 scenarios generated with 56 IAMsis analysed (IPCC, 2014b).

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 (Iyer et al., 2014; Wilson et al., 2013).

The methods used to derive pathways vary across IAMs (Kriegler et al., 2015). 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 pathway, 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 (Clarke et al., 2009; Edenhofer et al., 2010; Kriegler et al., 2015, 2014; van Vuuren et al., 2009) and occasionally evaluated against historical data (Guivarch et al., 2009; Wilson et al., 2013).

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

[2] We chose this study as it is freely available online (IIASA, 2014), other recent studies such as EMF27 (Tavoni et al., 2014) 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.

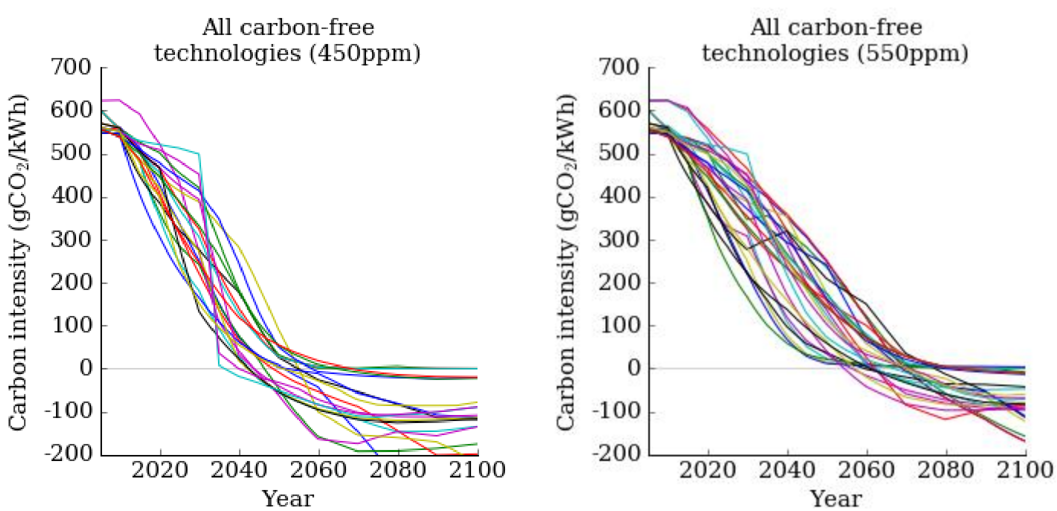
constructed by dividing carbon dioxide emissions from electricity generation by total electricity generation per scenario, model, region, and time step.

3. Results

3.1. Climate stabilization requires zero-carbon electricity

For the AMPERE study, IAMs were run under the constraint that final GHG atmospheric concentration should not exceed 450-ppm CO_2-eq — Meinshausen et al. (2009) estimate such concentration leads to 63-92% probability of remaining below +2°C by 2100. Figure 1 presents the projected carbon intensity of the global electricity generation in this scenario. It shows that all models project a drastic decrease in carbon intensity by the end of the century.

Most trajectories in this scenario fall below zero-carbon electricity. Indeed, this scenario assumes that the technologies able to generate low-carbon electricity are widely available — such technologies include mainly wind, solar, hydro, biomass, nuclear and carbon capture and storage (Smith et al., 2009).[3] Among them, bio-energy with carbon capture and storage (BECCS), the burning of biomass in power plants in connection with the long-term storage of resulting CO_2, allows to produce electricity with negative net GHG emissions (Kriegler et al., 2014; Tavoni and Socolow, 2013).[4] When BECCS is available, the least-cost strategy to achieve global carbon neutrality is to eventually generate negative-emission electricity thereby offsetting previous overshoot emissions or emissions from other sectors of the economy that are more difficult to decarbonize.



3 The optimal technology mix may also depend on environmental factors beyond the limitations of CO_2 emissions, such as air or water quality (Ou et al., 2018).

4 Plants extract carbon dioxide from the atmosphere as they grow.

Figure 1: Carbon content of electricity at the global scale in two scenarios: (left) 450-ppm stringent GHG concentration target (consistent with +2◦C); (right) 550-ppm less stringent GHG concentration target (consistent with +2-3◦C). Each thin line corresponds to the pathway simulated by one integrated assessment model (the reported carbon intensity for 2005-2010 varies among IAMs because they use different scopes and sources of historical data for calibration). In both cases, bio-energy with carbon capture and storage (BECCS) allows to reduce the carbon content of electricity to below-zero levels by the end of the century.

Stabilizing GHG concentration around 450 ppm would require efforts by all countries at a level that may be difficult to achieve in time (Guivarch and Hallegatte, 2013; Luderer et al., 2013; Stocker, 2013). AMPERE considered the effect of a less stringent concentration target: 500-ppm CO2-eq — generally admitted to be consistent with a +2-3◦C warming, and still reasonable probability of remaining below +2◦C (Meinshausen et al., 2009). If low-carbon technologies are still assumed to be widely available, pathways to this easier climate target also entail a decrease of the global carbon intensity to negative levels (Figure 3b).

The large-scale feasibility and desirability of BECCS is controversial, given the potential impact on land use, food production, freshwater availability, and the uncertain availability of suitable geological storage sites (Smith et al., 2016; Williamson, 2016). These aspects were not fully considered in AMPERE. The next section shows, however, that BECCS is not a pre-requisite for near-zero carbon electricity generation in the second part of the 21st century.

3.2. Near-zero-carbon electricity does not require all carbon-free technologies to be available

One scenario in AMPERE sets a 550-ppm CO2-eq stabilization target and assumes no further deployment of nuclear power after existing plants are decommissioned (for instance for social acceptability reasons) and assuming CCS never reaches market deployment. The decrease in carbon intensity of electricity holds at the global level under these assumptions (Figure 2). The trajectories in this sample exhibit an average of more than 95% reduction in carbon intensity, reaching less than 50 gCO2/kWh by 2100, while only one outlier pathway does not fall below 100 gCO2/kWh.

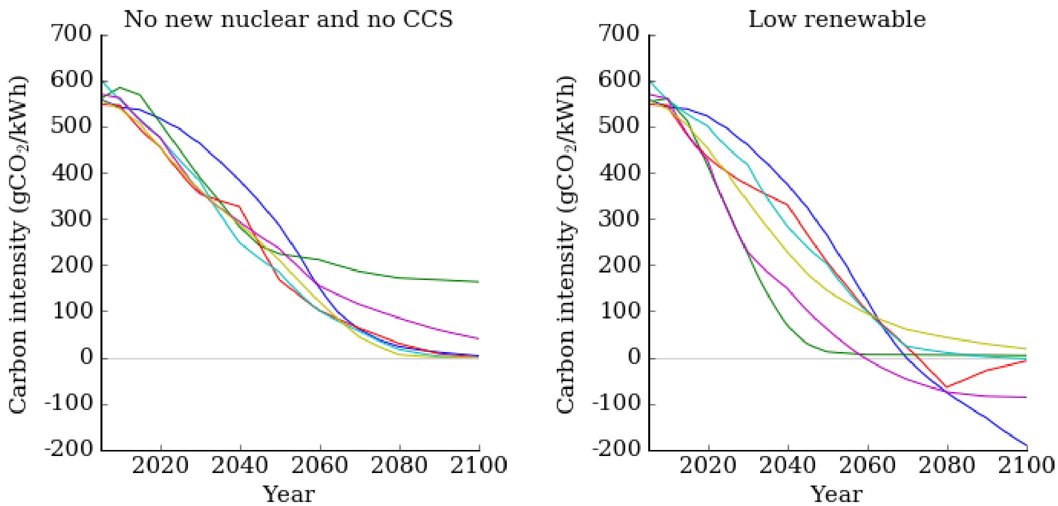


Figure 2: Decarbonization of global electricity in two 550 ppm scenarios (consistent with +2-3°C): (left) without new nuclear or carbon capture; (right) with low potential for renewable power. In both cases, the carbon content of electricity is reduced to near- or below-zero levels by the end of the century.

AMPERE also explored scenarios where CCS and nuclear are widely available, but renewable energy technologies (biomass, wind and photovoltaic power technologies) are constrained. Figure 2 reports the pathways of the carbon content of electricity in this case — they can still decrease to near-zero or even negative levels by the end of the century.

3.3. Decarbonization of electricity generation happens in all modelled countries or regions

According to pathways in AMPERE (which includes data at country or regional level), a decrease in the carbon content of electricity is feasible in every region of the world. Figure 3 reports the pathways towards carbon free electricity as simulated in AMPERE for China and India, two countries with high initial emissions from power generation, and for the EU and US, where electricity is already less carbon-intensive.

Here, the scenario that is least favourable to low-carbon electricity is considered, both in terms of the concentration target (550 ppm) and in terms of technology availability (no replacement of nuclear capacities and no CCS allowed). In every region, the average carbon intensity decreases steadily during the 21st century, and falls below 100 gCO2/kWh in 2100 in every simulation. Detailed pathways for these regions with different technology portfolios are displayed in the Appendix.

These figures suggest that electrification is an effective option to reduce long-term emissions in every region. In other words, the policy-relevant question is not whether to electrify, but when to do it, as discussed in the next section.

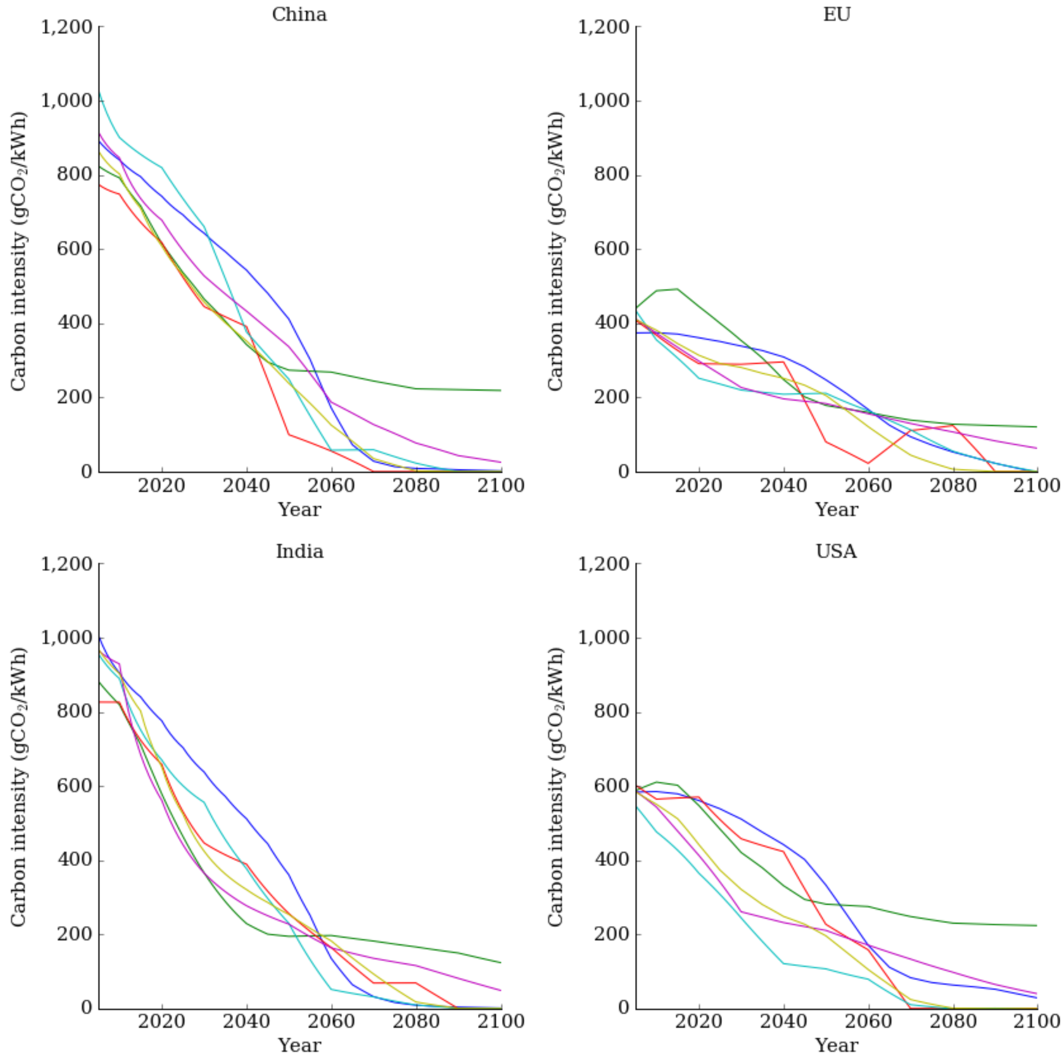


Figure 3: Carbon intensity in China, Europe, India and the US in AMPERE's 550 ppm (consistent with +2-3◦C), technology-pessimistic (no nuclear, no CCS) scenario.

3.4. Application to the assessment of electric vehicles as an emission reduction measure

In this section, the relevance of electric vehicles as a GHG emission reduction policy is assessed based on the pathways for the carbon intensity of electricity described above. Whether electric vehicles reduce GHG emissions depends on the carbon intensity of the vehicles they replace, and on the carbon intensity of electricity used to fuel them.

The carbon intensity of baseline vehicles is based on existing and enacted standards on energy efficiency (such as the CAFE standards in the US) or carbon emissions (such as the NEDC standards in Europe) of new personal cars. Yang and Bandivadekar (2017) provide a harmonized global database of these norms, converted into comparable equivalent norms of carbon emissions at the tailpipe, measured in gCO2/km. Six of the jurisdictions covered in the

AMPERE database also have norms for new vehicles: Brazil, China, EU, India, Japan, and USA.

The carbon intensity of electric vehicles is taken from a review by the US Environmental Protection Agency (EPA, 2018), which gathers data on electric vehicles for sale in the US. Both the median and the mean electric car consume 20kWh/100km. A simple way to assess well-to-wheel emissions of electric vehicles is to multiply their energy consumption and the current carbon content of electricity in different places. However, rather than reducing carbon emissions immediately, the point of promoting a switch to electric mobility is to put the economy on track towards a transition to zero carbon (Vogt-Schilb and Hallegatte, 2017). The effectiveness of doing so will depend not only on the current, but also on the future carbon content of electricity (Bauer et al., 2015).

Here, future emissions from electric vehicles are assessed using the carbon content of electricity in the Ampere 550 ppm technology-pessimistic scenarios (this is the worst-case scenario for electric vehicles) and the 450 ppm technology-optimistic scenarios (the best case scenario). The resulting figures are compared to the emission norms for new vehicles in each jurisdiction. To be consistent in the computation of well-to-wheel emissions, 15% is added to the norms to account for losses in refining and transportation of fuel, and 20% to electric vehicles emissions to account for transformation, distribution and recharging losses, following (Vogt-Schilb et al., 2013).

Figure 4 shows the result of this analysis. In Brazil, EU, and Japan, the carbon content of electricity is already low enough for electric vehicles to reduce emissions compared to the average vehicle that would just comply with the norm. In all climate-stabilization scenarios considered here, the carbon content of electricity would stay stable or decease over time. In all the projections and according to all models, the results suggest that electric vehicles would emit less carbon emissions than the norm over the next couple of decades.

In India, the situation is more nuanced. The carbon content of electricity is currently too high for electric vehicles to emit less carbon dioxide than conventional fuel vehicles fulfilling carbon emission norms. Only if the carbon content decreases as fast as the most optimistic models projection, would electric cars reduce emissions by the middle of next decade. Note that switching to electric vehicles *en masse* will likely take more than 10 years, and the government of India may have policy instruments at its disposal to enforce that the carbon content of electricity decreases as fast as in the more optimistic scenarios compiled in AMPERE. This suggests that a well-designed and properly enforced integrated power-transport strategy in India could ensure that electric vehicles are used to reduce emissions over the next decade.

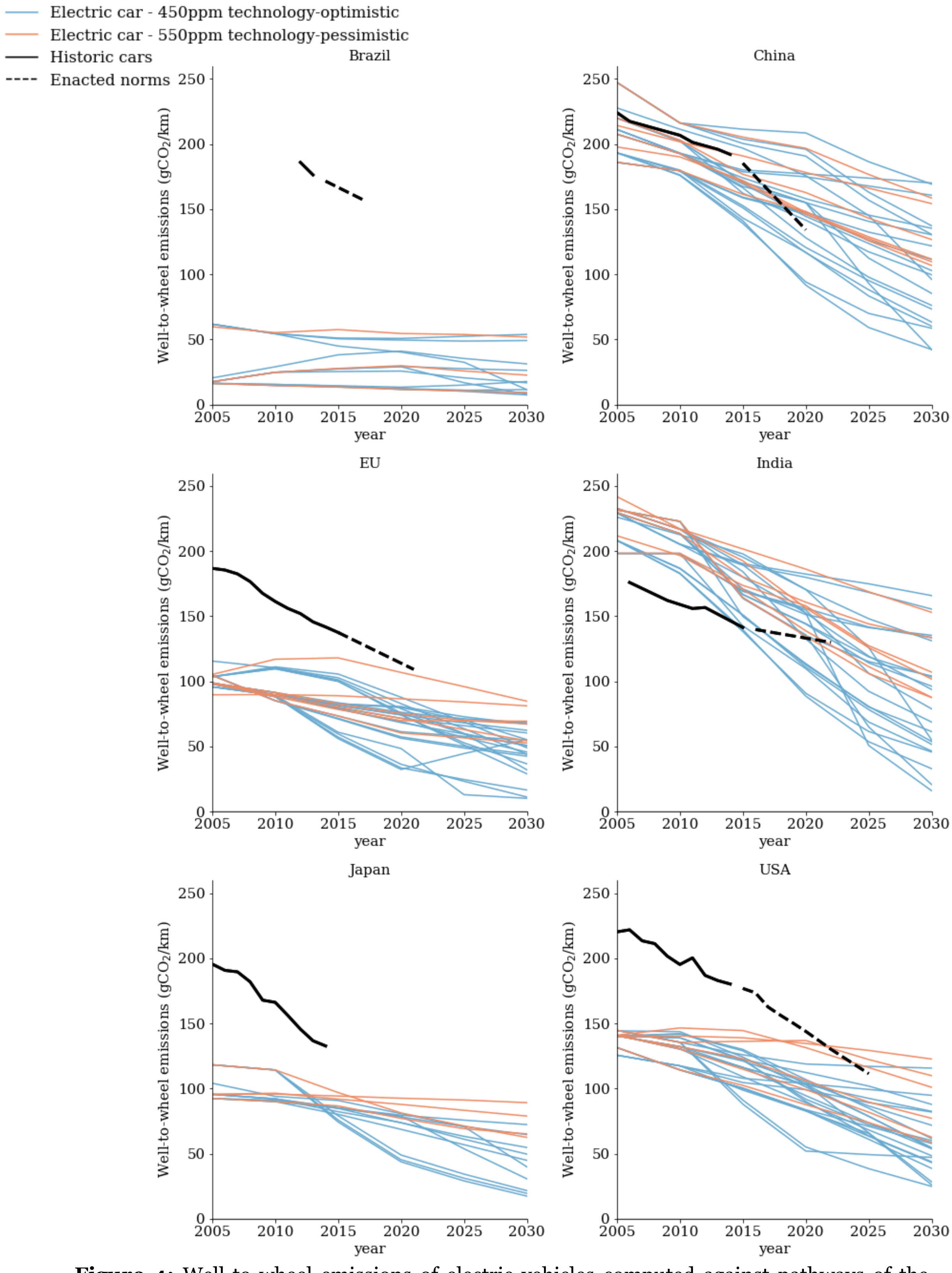


Figure 4: Well-to-wheel emissions of electric vehicles computed against pathways of the carbon content of electricity extracted from AMPERE and well-to-wheel emissions of an internal combustion engine vehicle fulfilling the maximum emission norms in its jurisdiction computed against Yang and Bandivadekar (2017).

In China, the situation is similar to India, but starting from diverging views on the current carbon content of electricity across models. This may reflect different data sources used by modellers. Notably, the "model uncertainty" on the current carbon content of electricity in China seems smaller than the modelled possibility range for 2030, suggesting again that policy choices today shape the relevance of electric vehicles as climate mitigation tools for the next decades. In this case, no definitive answer to the relevance of electric vehicles emerges from this exercise, which only assesses possible impacts on carbon emissions. Other reasons to adopt electric cars may be appealing to China, such as industrial policy objectives and clean air objectives at the city level.

Finally, in the USA the average carbon content of electricity today is clearly low enough for electric vehicles to outperform carbon dioxide emission standards. However, if standards for new vehicles keep tightening over time, electric cars will only remain below the standard if the carbon content of electricity decreases in a fashion consistent with the 450 ppm scenarios, or as fast as it does in the more optimistic 550 ppm scenarios.

4. Discussion and conclusion

The pathways towards clean electricity reported here should be interpreted cautiously. They do not entail any normative prescription of the level of efforts that any specific country should affect to climate change mitigation. What they show is a consensus among state-of-the-art integrated assessment models: cost-effective climate stabilization requires near-zero carbon electricity in every major country/region of the world. This robust finding is a technical one, which disregards any consideration of the burden sharing of emission reductions: independently of who is or should be paying for it, the cheapest strategy to achieve climate stabilization includes decarbonization of the power supply.

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 Figure 14 in the Appendix shows that the findings from AMPERE are consistent with the wider IPCC database of decarbonization pathways (IPCC, 2014b). Nonetheless, previous studies have documented the risk of selection bias in IAM reviews, as results are not always reported when targets are unachievable (Tavoni and Tol, 2010). 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).[5] This hints at the potential difficulty of reaching a stringent climatic target if the development of BECCS is constrained (Bibas and Méjean, 2014; Rose et al., 2014; Tavoni and Socolow, 2013).

The second limitation comes from the fact that IAMs might imperfectly account for several barriers to the decarbonization of power generation (Iyer et al., 2014). With a large penetration of intermittent renewable energies, ensuring the stability of the power system could require substantial investments that may not be accurately captured by IAMs (Brouwer et al., 2016). Also, some low-carbon technologies may require building wider distribution and transmission networks to connect remote energy sources or production locations to end-users (renewable energies and nuclear) and transportation infrastructure to carbon sequestration sites (CCS). Finally, building public acceptance for a new technology, such as CCS, can further delay or prevent adoption (Vögele et al., 2018).[6]

Despite these limitations, this paper allows to highlight a consensus within the IAM community about the need for reaching zero-carbon electricity before the end of the century to meet climate-stabilization targets. Specifically, this paper has established that (1) all pathways consistent with global warming anywhere from 1.5°C to 3°C feature near-zero-carbon electricity before the end of the century; (2) near-zero-carbon electricity can be achieved even if some of the key low-carbon technologies (nuclear, carbon capture and storage, or renewable power) turn out to be unavailable; and (3) near-zero-carbon electricity can occur in every major country or region of the world.

The pathways of the carbon content of electricity reported here can be used outside the community of integrated assessment. As an example, the desirability of electric vehicle as a technology reducing GHG emissions was assessed based on these pathways. More generally, they can be used to inform the design of long-term emission reduction strategies.

Acknowledgements

We thank Mook Bangalore, Ruben Bibas, Laura Bonzanigo, Stéphane Hallegatte, Aurélie Méjean and Julie Rozenberg who provided useful comments. We thank AMPERE for producing and publishing the data used in this paper. Financial support from Institut de la Mobilité Durable (Renault and ParisTech) and École des Ponts ParisTech is gratefully acknowledged. The views expressed in this paper are the sole responsibility of the authors. They

[5] 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.

[6] Public opinion may be even more reluctant to back more ambitious geo-engineering decarbonization technologies. However, such technologies are not modelled in traditional IAMs, see Anasis et al. (2018).

do not necessarily reflect the views of the Inter-American Development Bank, its executive directors, or the countries they represent.

A version of this paper was published as: Audoly, Richard, Adrien Vogt-Schilb, Céline Guivarch, and Alexander Pfeiffer. "Pathways toward zero-carbon electricity required for climate stabilization." *Applied Energy* 225 (2018): 884-901.

References

Albino, V., Ardito, L., Dangelico, R.M., Messeni Petruzzelli, A., 2014. Understanding the development trends of low-carbon energy technologies: A patent analysis. Applied Energy 135, 836–854. https://doi.org/10.1016/j.apenergy.2014.08.012

Anasis, J.G., Khalil, M.A.K., Butenhoff, C., Bluffstone, R., Lendaris, G.G., 2018. A Combined Energy and Geoengineering Optimization Model (CEAGOM) for climate and energy policy analysis. Applied Energy 218, 246–255. https://doi.org/10.1016/j.apenergy.2018.02.145

Bataille, C., Waisman, H., Colombier, M., Segafredo, L., Williams, J., Jotzo, F., 2016. The need for national deep decarbonization pathways for effective climate policy. Climate Policy 16, S7–S26. https://doi.org/10.1080/14693062.2016.1173005

Bauer, C., Hofer, J., Althaus, H.-J., Del Duce, A., Simons, A., 2015. The environmental performance of current and future passenger vehicles: Life cycle assessment based on a novel scenario analysis framework. Applied Energy 157, 871–883. https://doi.org/10.1016/j.apenergy.2015.01.019

BBC, 2012. Electric cars "pose environmental threat." BBC News.

Bibas, R., Méjean, A., 2014. Potential and limitations of bioenergy for low carbon transitions. Climatic Change 123, 731–761. https://doi.org/10.1007/s10584-013-0962-6

Brouwer, A.S., van den Broek, M., Zappa, W., Turkenburg, W.C., Faaij, A., 2016. Least-cost options for integrating intermittent renewables in low-carbon power systems. Applied Energy 161, 48–74. https://doi.org/10.1016/j.apenergy.2015.09.090

Clarke, L., Edmonds, J., Krey, V., Richels, R., Rose, S., Tavoni, M., 2009. International climate policy architectures: Overview of the EMF 22 international scenarios. Energy Economics 31, S64–S81. https://doi.org/10.1016/j.eneco.2009.10.013

Collins, M., Knutti, R., Arblaster, J.M., Dufresne, J.-L., Fichefet, T., Friedlingstein, P., Gao, X., Gutowski, W.J., Johns, T., Krinner, G., 2013. Long-term climate change: Projections, commitments and irreversibility, in: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.

Doucette, R.T., McCulloch, M.D., 2011. Modeling the prospects of plug-in hybrid electric vehicles to reduce CO2 emissions. Applied Energy 88, 2315–2323. https://doi.org/10.1016/j.apenergy.2011.01.045

Edenhofer, O., Knopf, B., Barker, T., Baumstark, L., Bellevrat, E., Chateau, B., Criqui, P., Isaac, M., Kitous, A., Kypreos, S., others, 2010. The economics of low stabilization: Model comparison of mitigation strategies and costs. The Energy Journal 31, 11–48.

EPA, 2018. Compare Electric Cars [WWW Document]. URL https://www.fueleconomy.gov/feg/evsbs.shtml (accessed 3.5.18).

European Commission, 2011. A roadmap for moving to a competitive low carbon economy in 2050.
Fay, M., Hallegatte, S., Vogt-Schilb, A., Rozenberg, J., Narloch, U., Kerr, T., 2015. Decarbonizing Development: Three Steps to a Zero-Carbon Future. World Bank Publications, Washington DC, USA.
Graff Zivin, J.S., Kotchen, M.J., Mansur, E.T., 2014. Spatial and temporal heterogeneity of marginal emissions: Implications for electric cars and other electricity-shifting policies. Journal of Economic Behavior & Organization 107, Part, 248–268. https://doi.org/10.1016/j.jebo.2014.03.010
Guivarch, C., Hallegatte, S., 2013. 2°C or not 2°C? Global Environmental Change 23, 179–192. https://doi.org/10.1016/j.gloenvcha.2012.10.006
Guivarch, C., Hallegatte, S., Crassous, R., 2009. The resilience of the Indian economy to rising oil prices as a validation test for a global energy–environment–economy CGE model. Energy Policy 37, 4259–4266. https://doi.org/10.1016/j.enpol.2009.05.025
Gustavsson, L., Joelsson, A., 2010. Life cycle primary energy analysis of residential buildings. Energy and Buildings 42, 210–220. https://doi.org/10.1016/j.enbuild.2009.08.017
Hawkins, T.R., Gausen, O.M., Strømman, A.H., 2012a. Environmental impacts of hybrid and electric vehicles: A review. The International Journal of Life Cycle Assessment 17, 997–1014. https://doi.org/10.1007/s11367-012-0440-9
Hawkins, T.R., Singh, B., Majeau-Bettez, G., Strømman, A.H., 2012b. Comparative environmental life cycle assessment of conventional and electric vehicles. Journal of Industrial Ecology.
Hertwich, E.G., Gibon, T., Bouman, E.A., Arvesen, A., Suh, S., Heath, G.A., Bergesen, J.D., Ramirez, A., Vega, M.I., Shi, L., 2014. Integrated life-cycle assessment of electricity-supply scenarios confirms global environmental benefit of low-carbon technologies. Proceedings of the National Academy of Sciences 201312753.
IEA, 2017a. CO_2 Emissions From Fuel Combustion Highlights 2017.
IEA, 2017b. Energy Technology Perspectives 2017. http://dx.doi.org/10.1787/energy_tech-2017-en
IEA, 2014. Energy technology perspectives 2014: harnessing electricity's potential, International Energy Agency and Organisation for Economic Co-operation and Development. ed. OECD/IEA, Paris, France.
IIASA, 2014. AMPERE Public Database. International Institute for Applied Systems Analysis.
IPCC, 2014a. Summary for Policymakers, in: Climate Change 2014: Mitigation of Climate Change - Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (Eds.)]. Cambridge, United Kingdom and New York, {NY}, {USA}.
IPCC, 2014b. Annex II: Metrics and Methodology, in: Climate Change 2014, Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (Eds.)]. Cambridge, United Kingdom and New York, NY, USA.
IPCC, 2013. Summary for Policymakers, in: Climate Change 2013: The Physical Science Basis - Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, [Stocker, T.F., D.

Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (Eds.)]. Cambridge, United Kingdom and New York, {USA}.

Iyer, G., Hultman, N., Eom, J., McJeon, H., Patel, P., Clarke, L., 2014. Diffusion of low-carbon technologies and the feasibility of long-term climate targets. Technological Forecasting and Social Change. https://doi.org/10.1016/j.techfore.2013.08.025

Katrašnik, T., 2013. Impact of vehicle propulsion electrification on Well-to-Wheel CO2 emissions of a medium duty truck. Applied Energy 108, 236–247. https://doi.org/10.1016/j.apenergy.2013.03.029

Ke, W., Zhang, S., He, X., Wu, Y., Hao, J., 2017. Well-to-wheels energy consumption and emissions of electric vehicles: Mid-term implications from real-world features and air pollution control progress. Applied Energy 188, 367–377. https://doi.org/10.1016/j.apenergy.2016.12.011

Krey, V., Luderer, G., Clarke, L., Kriegler, E., 2014. Getting from here to there – Energy technology transformation pathways in the EMF 27 scenarios. Climatic Change 123, 369–382.

Kriegler, E., Riahi, K., Bauer, N., Schwanitz, V.J., Petermann, N., Bosetti, V., Marcucci, A., Otto, S., Paroussos, L., Rao, S., Arroyo Currás, T., Ashina, S., Bollen, J., Eom, J., Hamdi-Cherif, M., Longden, T., Kitous, A., Méjean, A., Sano, F., Schaeffer, M., Wada, K., Capros, P., P. van Vuuren, D., Edenhofer, O., 2015. Making or breaking climate targets: The AMPERE study on staged accession scenarios for climate policy. Technological Forecasting and Social Change 90, Part A, 24–44. https://doi.org/10.1016/j.techfore.2013.09.021

Kriegler, E., Weyant, J.P., Blanford, G.J., Krey, V., Clarke, L., Edmonds, J., Fawcett, A., Luderer, G., Riahi, K., Richels, R., Rose, S.K., Tavoni, M., Vuuren, D.P. van, 2014. The Role of Technology for Achieving Climate Policy Objectives: Overview of the EMF 27 study on global technology and climate policy strategies. Climatic Change 123, 353–367.

Lewis, A.M., Kelly, J.C., Keoleian, G.A., 2014. Vehicle lightweighting vs. electrification: Life cycle energy and GHG emissions results for diverse powertrain vehicles. Applied Energy 126, 13–20. https://doi.org/10.1016/j.apenergy.2014.03.023

Luderer, G., Bosetti, V., Jakob, M., Leimbach, M., Steckel, J.C., Waisman, H., Edenhofer, O., 2012. The Economics of Decarbonizing the Energy System: Results and insights from the RECIPE model intercomparison. Climatic Change 114, 9–37.

Luderer, G., Pietzcker, R.C., Bertram, C., Kriegler, E., Meinshausen, M., Edenhofer, O., 2013. Economic Mitigation Challenges: How further delay closes the door for achieving climate targets. Environmental Research Letters 8, 034033. https://doi.org/10.1088/1748-9326/8/3/034033

McCollum, D., Krey, V., Kolp, P., Nagai, Y., Riahi, K., 2014. Transport Electrification: A key element for energy system transformation and climate stabilization. Climatic Change 123, 651–664. https://doi.org/10.1007/s10584-013-0969-z

Meinshausen, M., Meinshausen, N., Hare, W., Raper, S.C.B., Frieler, K., Knutti, R., Frame, D.J., Allen, M.R., 2009. Greenhouse-gas emission targets for limiting global warming to 2* Celsius. Nature 458, 1158–1162. https://doi.org/10.1038/nature08017

Miotti, M., Supran, G.J., Kim, E.J., Trancik, J.E., 2016. Personal Vehicles Evaluated against Climate Change Mitigation Targets. Environ. Sci. Technol. 50, 10795–10804. https://doi.org/10.1021/acs.est.6b00177

Orsi, F., Muratori, M., Rocco, M., Colombo, E., Rizzoni, G., 2016. A multi-dimensional well-to-wheels analysis of passenger vehicles in different

regions: Primary energy consumption, CO2 emissions, and economic cost. Applied Energy 169, 197–209. https://doi.org/10.1016/j.apenergy.2016.02.039
Ou, Y., Shi, W., Smith, S.J., Ledna, C.M., West, J.J., Nolte, C.G., Loughlin, D.H., 2018. Estimating environmental co-benefits of U.S. low-carbon pathways using an integrated assessment model with state-level resolution. Applied Energy 216, 482–493. https://doi.org/10.1016/j.apenergy.2018.02.122
Peng, W., Yang, J., Lu, X., Mauzerall, D.L., 2018. Potential co-benefits of electrification for air quality, health, and CO2 mitigation in 2030 China. Applied Energy 218, 511–519. https://doi.org/10.1016/j.apenergy.2018.02.048
Pfeiffer, A., Millar, R., Hepburn, C., Beinhocker, E., 2016. The '2°C capital stock' for electricity generation: Committed cumulative carbon emissions from the electricity generation sector and the transition to a green economy. Applied Energy 179, 1395–1408. https://doi.org/10.1016/j.apenergy.2016.02.093
Ramesh, T., Prakash, R., Shukla, K.K., 2010. Life cycle energy analysis of buildings: An overview. Energy and Buildings 42, 1592–1600. https://doi.org/10.1016/j.enbuild.2010.05.007
Riahi, K., Kriegler, E., Johnson, N., Bertram, C., den Elzen, M., Eom, J., Schaeffer, M., Edmonds, J., Isaac, M., Krey, V., Longden, T., Luderer, G., Méjean, A., McCollum, D.L., Mima, S., Turton, H., van Vuuren, D.P., Wada, K., Bosetti, V., Capros, P., Criqui, P., Hamdi-Cherif, M., Kainuma, M., Edenhofer, O., 2015. Locked into Copenhagen pledges - Implications of short-term emission targets for the cost and feasibility of long-term climate goals. Technological Forecasting and Social Change 90, 8–23. https://doi.org/10.1016/j.techfore.2013.09.016
Richardson, D.B., 2013. Electric Vehicles and the Electric Grid: A review of modeling approaches, impacts, and renewable energy integration. Renewable and Sustainable Energy Reviews 19, 247–254. https://doi.org/10.1016/j.rser.2012.11.042
Rogelj, J., Schaeffer, M., Meinshausen, M., Knutti, R., Alcamo, J., Riahi, K., Hare, W., 2015. Zero emission targets as long-term global goals for climate protection. Environ. Res. Lett. 10, 105007. https://doi.org/10.1088/1748-9326/10/10/105007
Rose, S.K., Kriegler, E., Bibas, R., Calvin, K., Popp, A., van Vuuren, D.P., Weyant, J., 2014. Bioenergy in energy transformation and climate management. Climatic Change 123, 477–493. https://doi.org/10.1007/s10584-013-0965-3
Sachs, J., Tubiana, L., Guerin, E., Waisman, H., Mas, C., Colombier, M., Schmidt-Traub, G., 2014. Pathways to deep decarbonization. New York and Paris.
SEMARNAT, INECC, 2016. Mexico's Climate Change Mid-Century Strategy. Ministry of Environment and Natural Resources (SEMARNAT) and National Institute of Ecology and Climate Change (INECC).
Shi, W., Ou, Y., Smith, S.J., Ledna, C.M., Nolte, C.G., Loughlin, D.H., 2017. Projecting state-level air pollutant emissions using an integrated assessment model: GCAM-USA. Applied Energy 208, 511–521. https://doi.org/10.1016/j.apenergy.2017.09.122
Sioshansi, R., Denholm, P., 2009. Emissions impacts and benefits of plug-in hybrid electric vehicles and vehicle-to-grid services. Environmental Science & Technology 43, 1199–1204. https://doi.org/10.1021/es802324j
Smith, H.J., Fahrenkamp-Uppenbrink, J., Coontz, R., 2009. Clearing the Air: Introduction to the special issue on carbon capture and sequestration. Science 325, 1641. https://doi.org/10.1126/science.325_1641
Smith, P., Davis, S.J., Creutzig, F., Fuss, S., Minx, J., Gabrielle, B., Kato, E., Jackson, R.B., Cowie, A., Kriegler, E., van Vuuren, D.P., Rogelj, J., Ciais, P., Milne, J.,

Canadell, J.G., McCollum, D., Peters, G., Andrew, R., Krey, V., Shrestha, G., Friedlingstein, P., Gasser, T., Grübler, A., Heidug, W.K., Jonas, M., Jones, C.D., Kraxner, F., Littleton, E., Lowe, J., Moreira, J.R., Nakicenovic, N., Obersteiner, M., Patwardhan, A., Rogner, M., Rubin, E., Sharifi, A., Torvanger, A., Yamagata, Y., Edmonds, J., Yongsung, C., 2016. Biophysical and economic limits to negative CO2 emissions. Nature Clim. Change 6, 42–50. https://doi.org/10.1038/nclimate2870
Stocker, T.F., 2013. The Closing door of climate targets. Science 339, 280–282.
Sugiyama, M., 2012. Climate change mitigation and electrification. Energy Policy 44, 464–468.
Tavoni, M., Kriegler, E., Riahi, K., van Vuuren, D.P., Aboumahboub, T., Bowen, A., Calvin, K., Campiglio, E., Kober, T., Jewell, J., Luderer, G., Marangoni, G., McCollum, D., van Sluisveld, M., Zimmer, A., van der Zwaan, B., 2014. Post-2020 climate agreements in the major economies assessed in the light of global models. Nature Climate Change 5. https://doi.org/10.1038/nclimate2475
Tavoni, M., Socolow, R., 2013. Modeling Meets Science and Technology: An introduction to a special issue on negative emissions. Climatic Change 118, 1–14. https://doi.org/10.1007/s10584-013-0757-9
Tavoni, M., Tol, R.S.J., 2010. Counting only the hits? The risk of underestimating the costs of stringent climate policy. Climatic change 100, 769–778.
Thomson, M.J., Evenson, E.J., Kempe, M.J., Goodfellow, H.D., 2000. Control of Greenhouse Gas Emissions from Electric Arc Furnace Steelmaking: Evaluation methodology with case studies. Ironmaking & Steelmaking 27, 273–279. https://doi.org/10.1179/030192300677552
van Vuuren, D.P., Hoogwijk, M., Barker, T., Riahi, K., Boeters, S., Chateau, J., Scrieciu, S., van Vliet, J., Masui, T., Blok, K., Blomen, E., Kram, T., 2009. Comparison of top-down and bottom-up estimates of sectoral and regional greenhouse gas emission reduction potentials. Energy Policy 37, 5125–5139. https://doi.org/10.1016/j.enpol.2009.07.024
Veysey, J., Octaviano, C., Calvin, K., Martinez, S.H., Kitous, A., McFarland, J., van der Zwaan, B., 2014. Pathways to Mexico's climate change mitigation targets: A multi-model analysis. Energy Economics 56, 587–599. https://doi.org/10.1016/j.eneco.2015.04.011
Vögele, S., Rübbelke, D., Mayer, P., Kuckshinrichs, W., 2018. Germany's "No" to carbon capture and storage: Just a question of lacking acceptance? Applied Energy 214, 205–218. https://doi.org/10.1016/j.apenergy.2018.01.077
Vogt-Schilb, A., Guivarch, C., Hourcade, J.-C., 2013. Les véhicules électrifiés réduiront-ils les émissions de carbone? Revue de l'énergie 5–11.
Vogt-Schilb, A., Hallegatte, S., 2017. Climate Policies and Nationally Determined Contributions: Reconciling the Needed Ambition with the Political Economy. WIREs Energy Environ e256. https://doi.org/10.1002/wene.256
Williams, J.H., DeBenedictis, A., Ghanadan, R., Mahone, A., Moore, J., Morrow, W.R., Price, S., Torn, M.S., 2012. The Technology Path to Deep Greenhouse Gas Emissions Cuts by 2050: The pivotal role of electricity. Science 335, 53–59.
Williamson, P., 2016. Scrutinize CO2 removal methods. Nature 530, 153–155.
Wilson, C., Grubler, A., Bauer, N., Krey, V., Riahi, K., 2013. Future Capacity Growth of Energy Technologies: Are scenarios consistent with historical evidence? Climatic Change 118, 381–395. https://doi.org/10.1007/s10584-012-0618-y
WRI, 2018. CAIT 2.0: WRI's climate data explorer. World Resources Institute http://cait2.wri.org/wri/. https://doi.org/10.1016/S0301-4215(02)00192-1

Yang, Z., Bandivadekar, A., 2017. Light-duty vehicle greenhouse gas and fuel economy standards: 2017 Global update. International Council on Clean Transportation, Washington.
Zabalza Bribián, I., Aranda Usón, A., Scarpellini, S., 2009. Life Cycle Assessment in Buildings: State-of-the-art and simplified LCA methodology as a complement for building certification. Building and Environment 44, 2510–2520. https://doi.org/10.1016/j.buildenv.2009.05.001

Appendix: Additional Figures

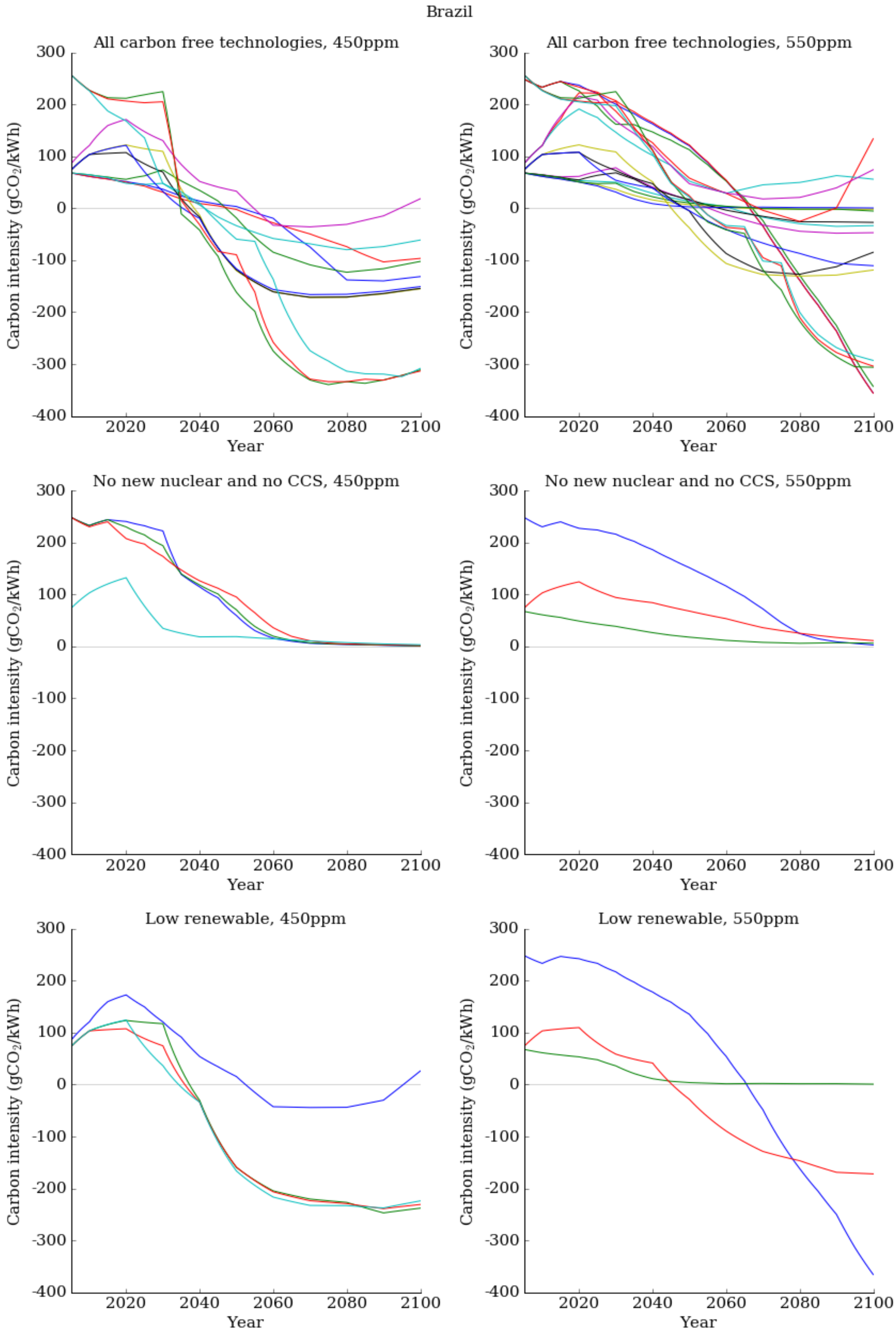


Figure 5: Carbon content of electricity under in **Brazil** (AMPERE database).

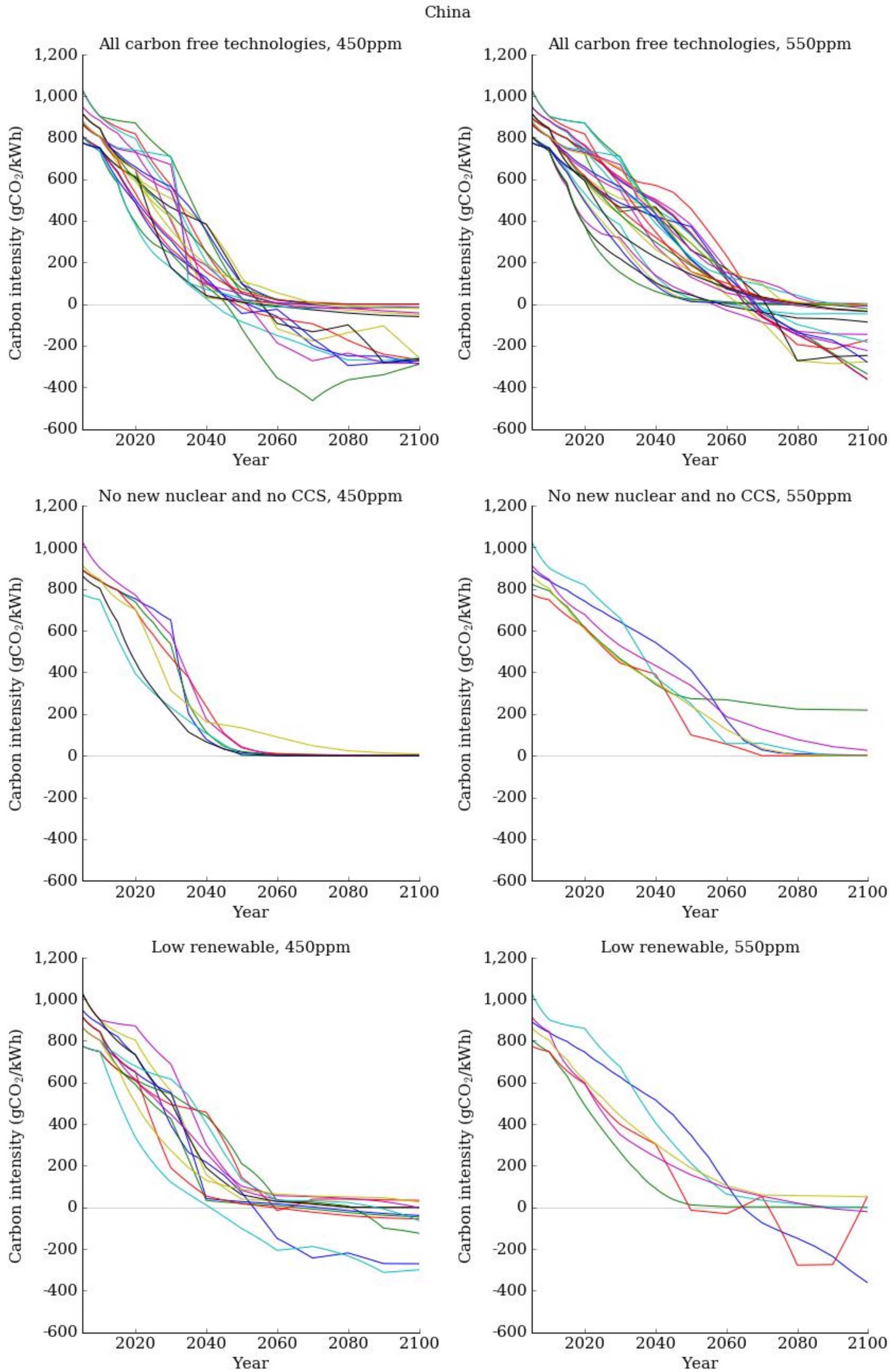


Figure 6: Carbon content of electricity in **China** (AMPERE database).

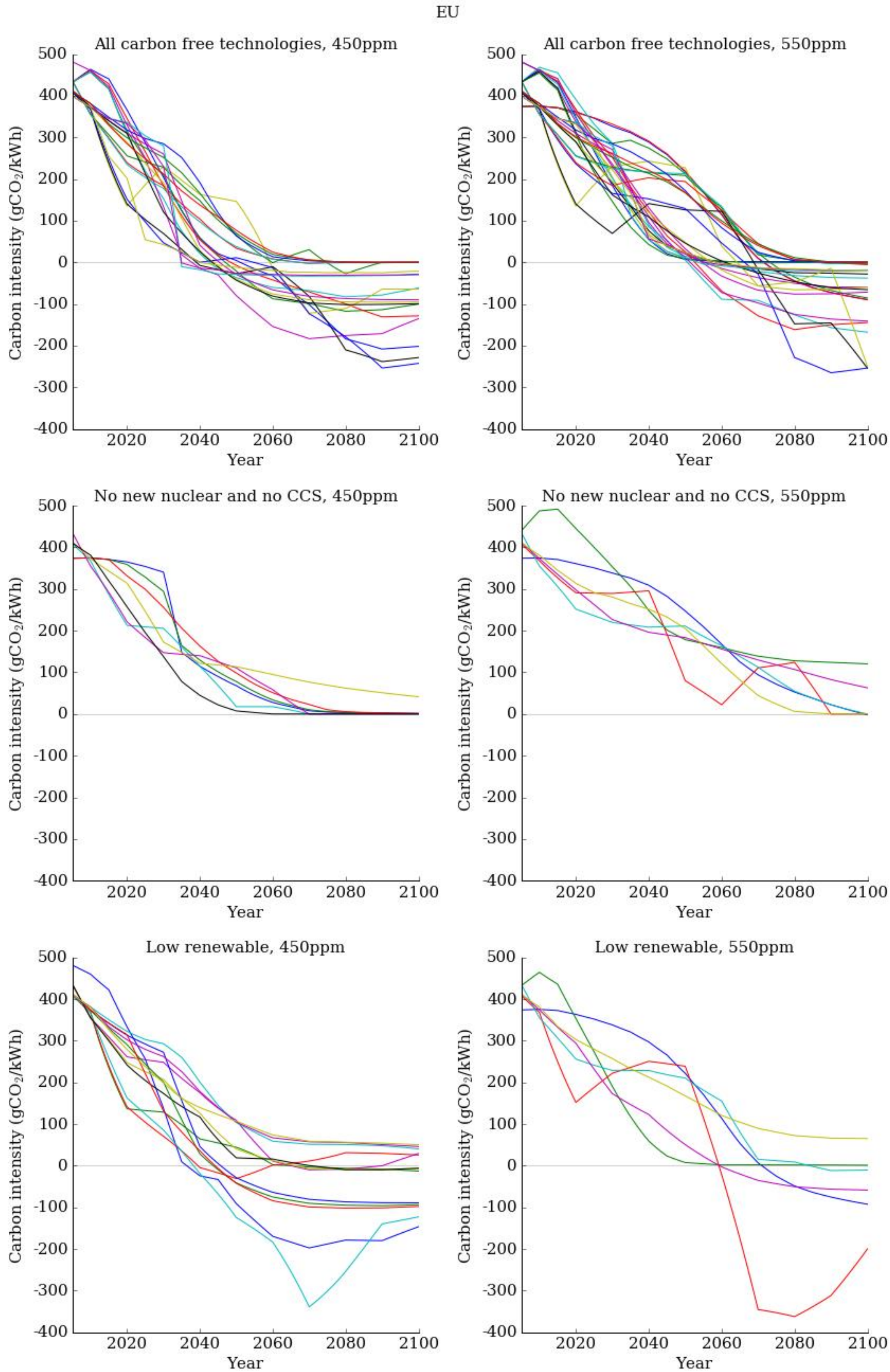


Figure 7: Carbon content of electricity in the **EU** (AMPERE database).

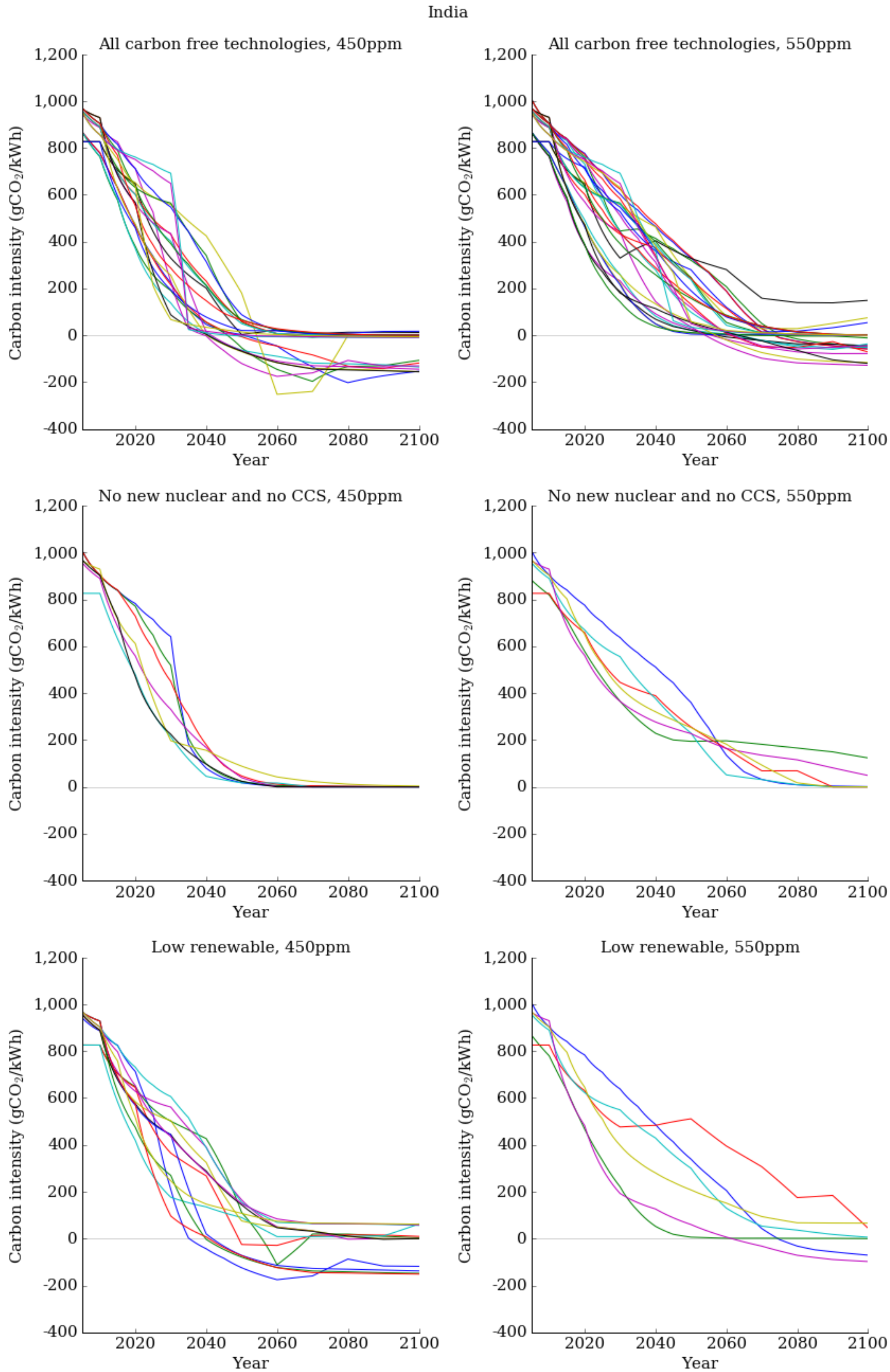


Figure 8: Carbon content of electricity in **India** (AMPERE database).

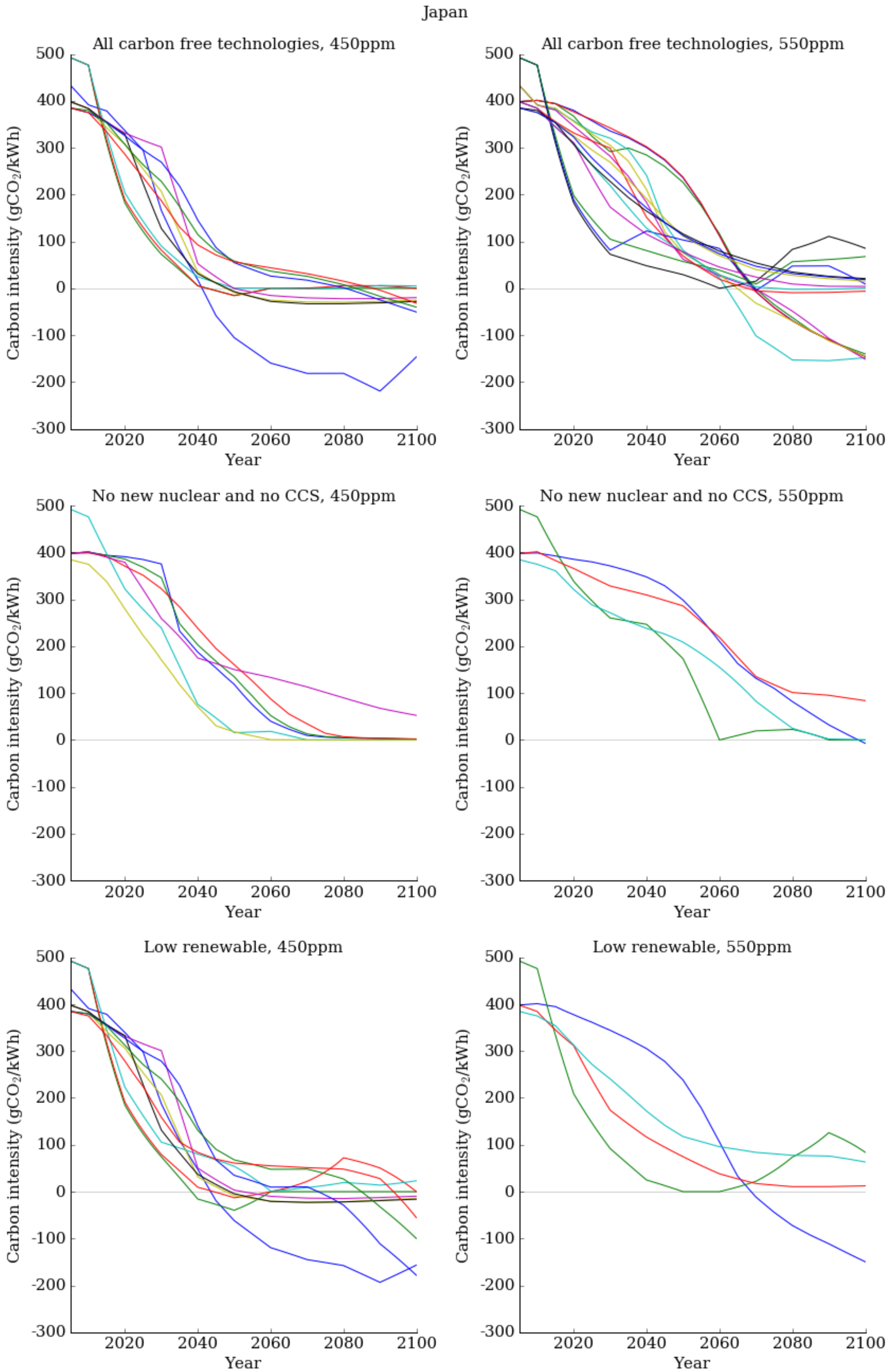


Figure 9: Carbon content of electricity in Japan (AMPERE database).

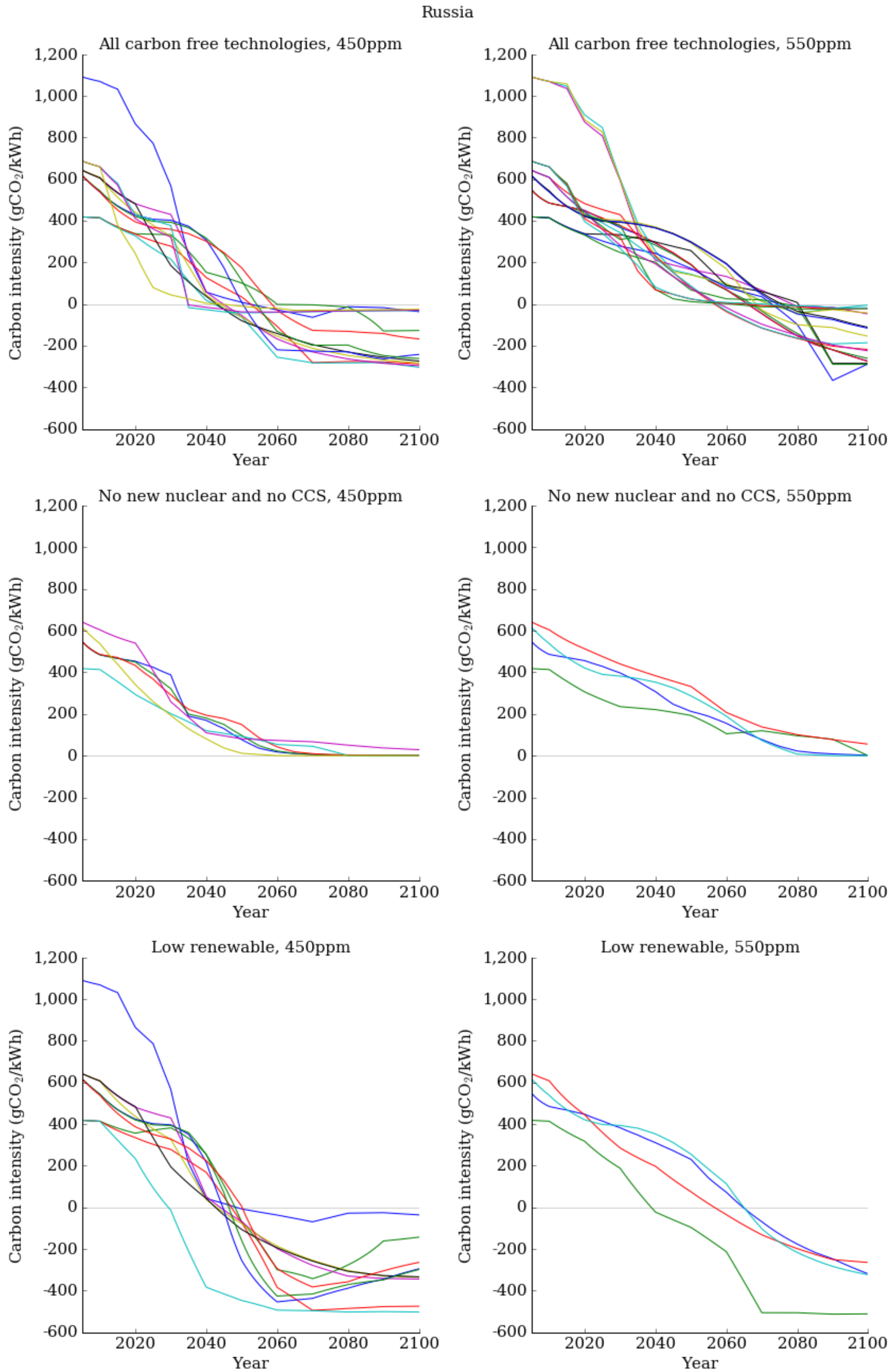


Figure 10: Carbon content of electricity in **Russia** (AMPERE database).

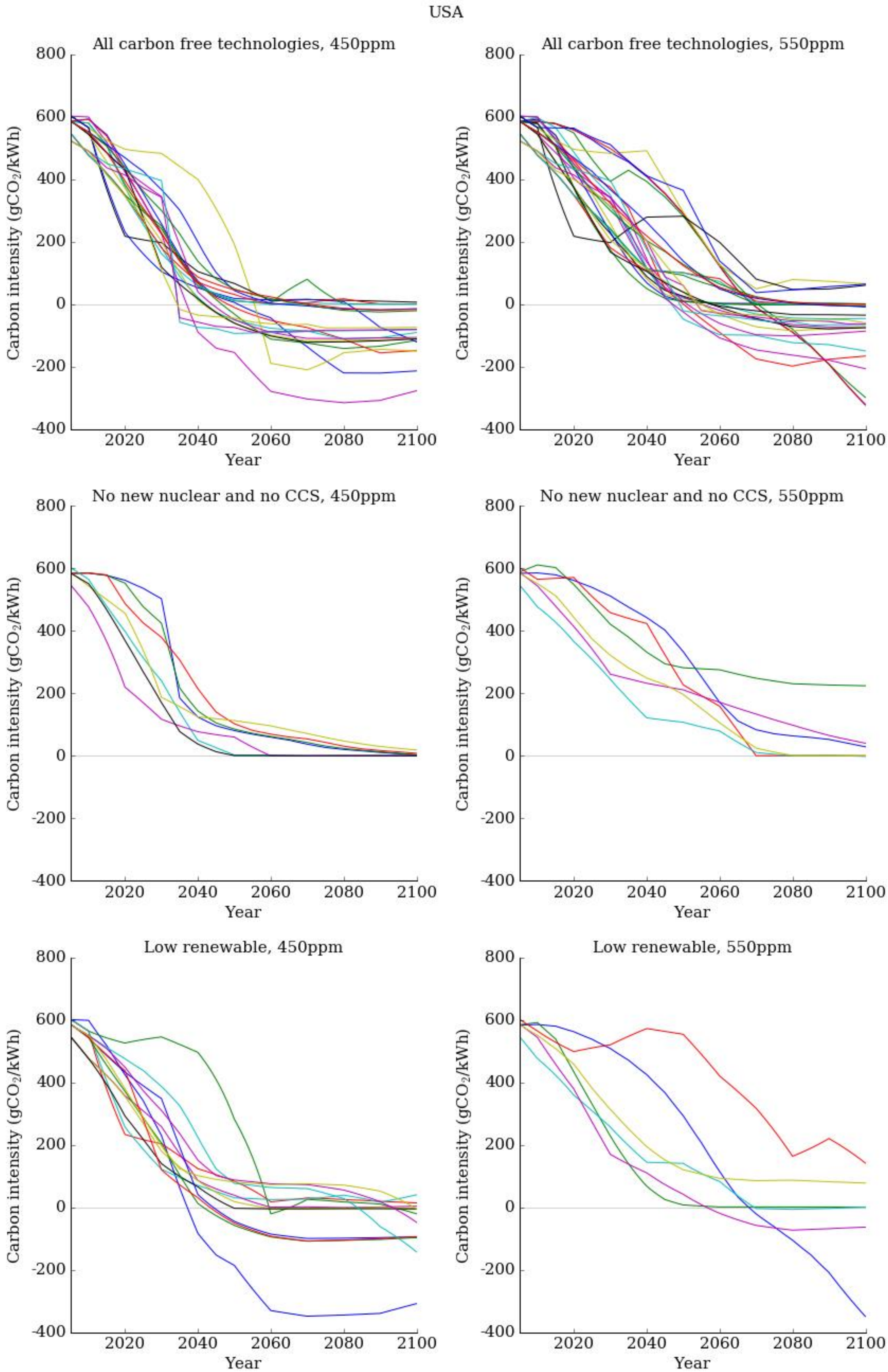


Figure 11: Carbon content of electricity in **USA** (AMPERE database).

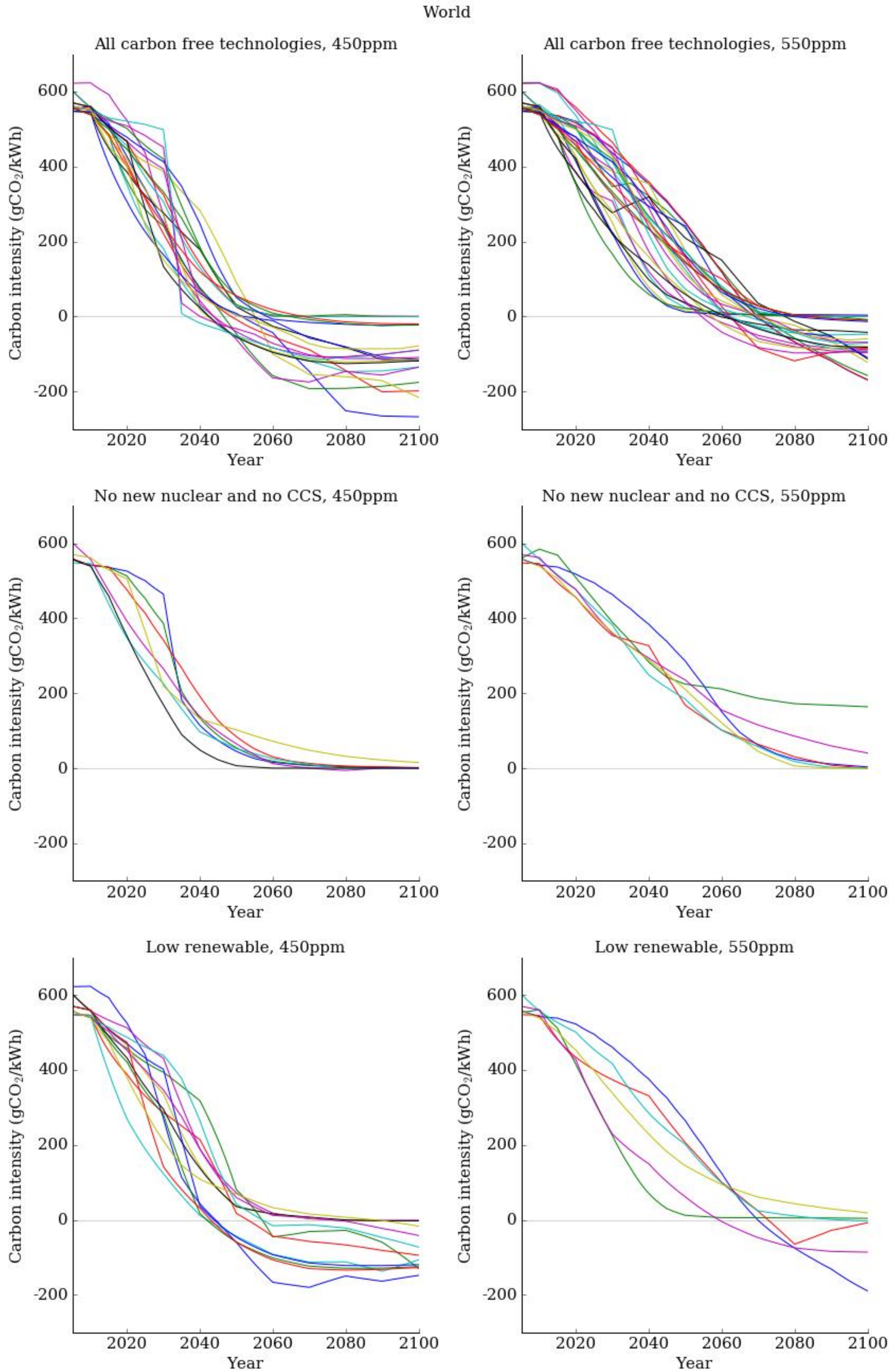


Figure 12: Carbon intensity of electricity at the **global level** (AMPERE database).

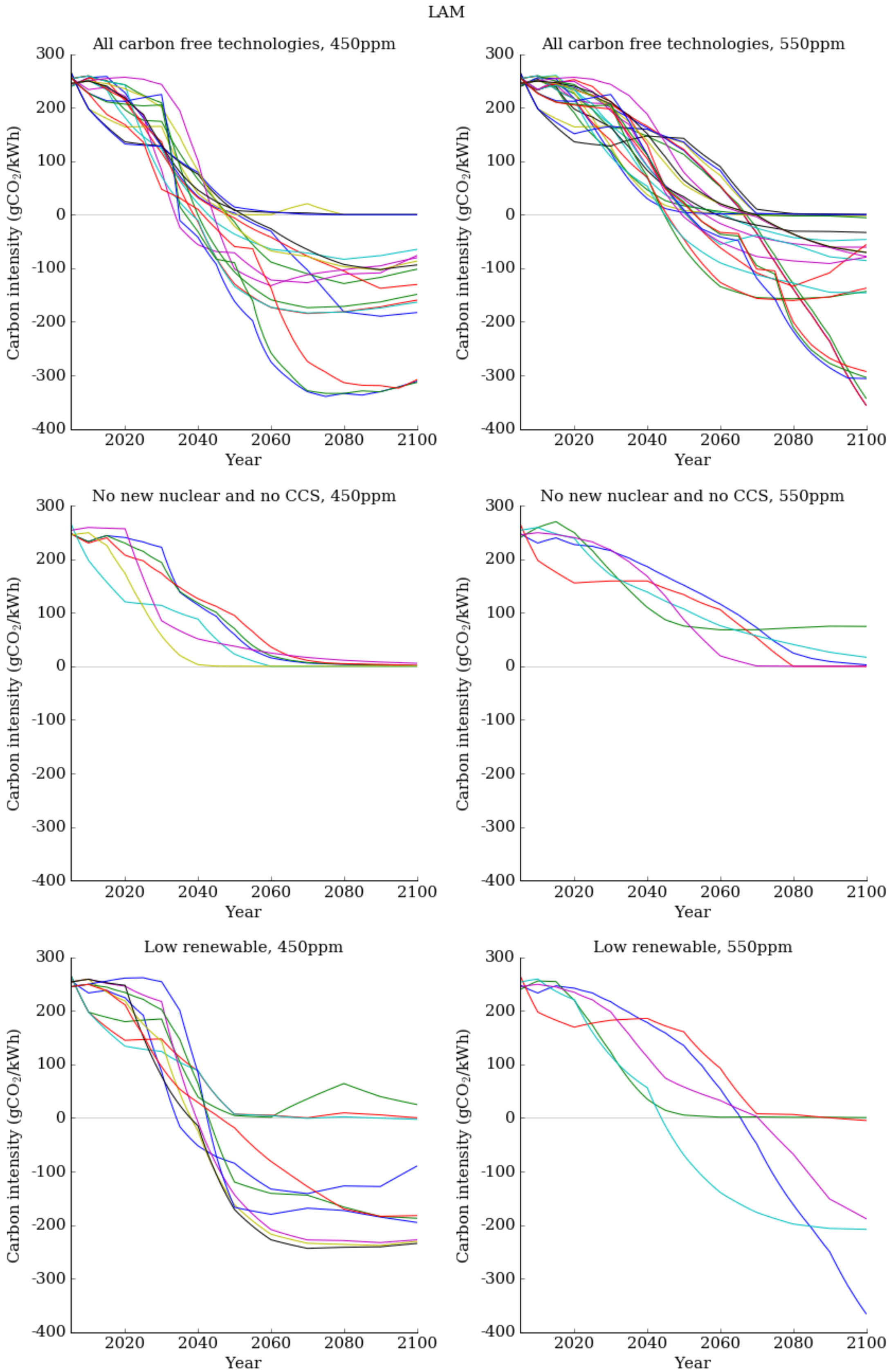


Figure 13: Carbon intensity of electricity in **Latin America and the Caribbean** (AMPERE database).

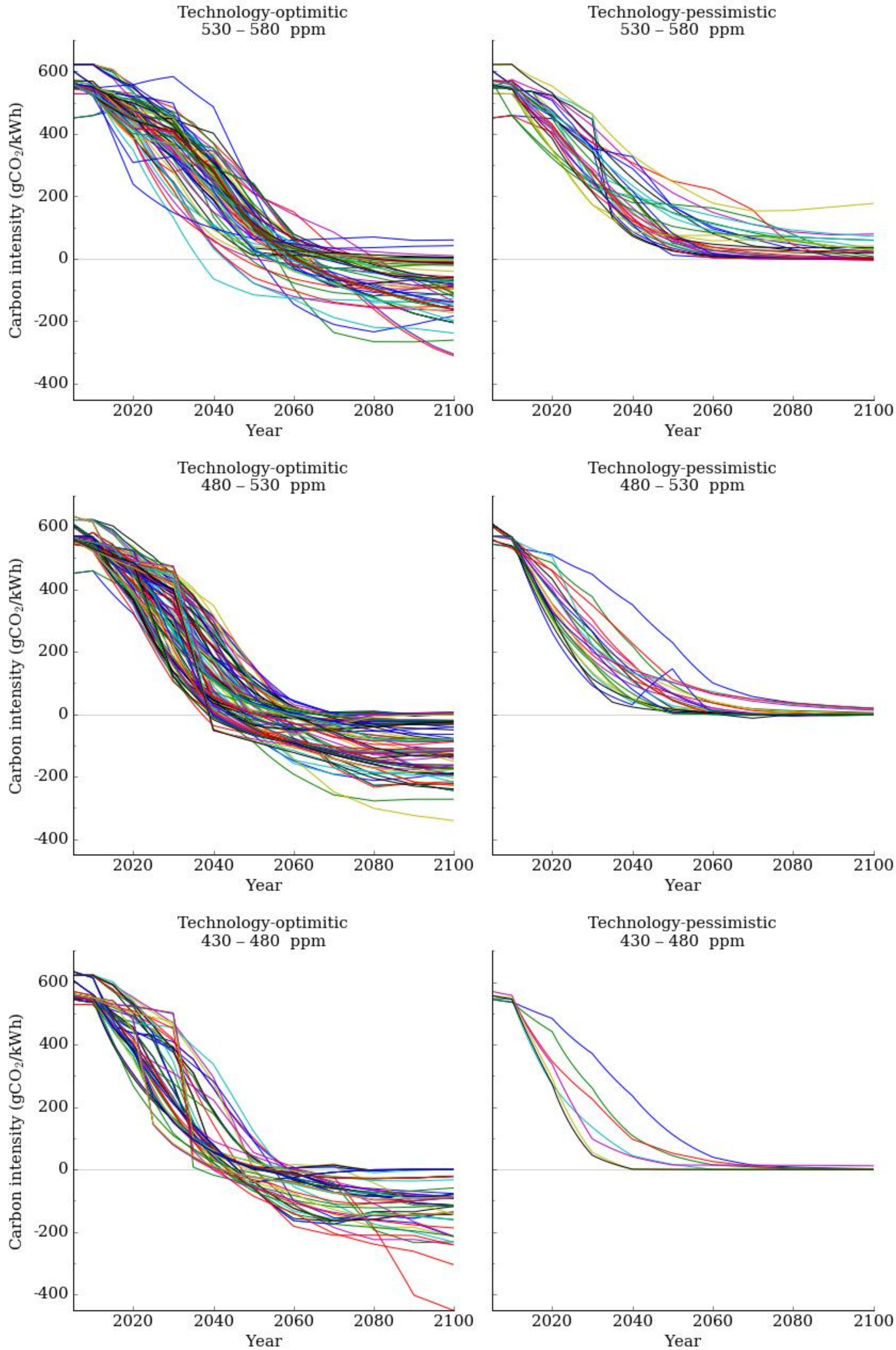


Figure 14: Carbon intensity of electricity under different GHG concentration targets and different technology assumption at the global level from IPCC AR5 database (IPCC, 2014b).