# Pathways toward Zero-Carbon Electricity Required for Climate Stabilization

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**Abstract**

This paper covers three policy-relevant aspects of the carbon content of electricity that are well established among integrated assessment models but under-discussed in the policy debate. First, climate stabilization at any level from 2°C to 3°C requires electricity to be almost carbon-free by the end of the century. As such, the question for policy makers is not whether to decarbonize electricity but when 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. In addition, this paper provides cost-effective pathways of the carbon content of electricity — computed from the results of AMPERE, a recent integrated assessment model comparison study. These pathways may be used to benchmark existing decarbonization targets, such as those set by the European Energy Roadmap or the Clean Power Plan in the United States, or inform new policies in other countries. These pathways can also be used to assess the desirable uptake rates of electrification technologies, such as electric and plug-in hybrid vehicles, electric stoves and heat pumps, or industrial electric furnaces.

*Keywords:* climate change mitigation; life cycle assessment; power supply; carbon intensity *JEL:* Q01; Q4; Q54; Q56

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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 12 $GtCO_2$/yr, about 28% 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, today's road transportation and housing sectors account together for about 16% of total emissions; and industrial energy consumption, mainly used to produce heat or motion, accounts for an additional 18% (IEA, 2012; WRI, 2014). Technologies such as electric vehicles, heat pumps, electric furnaces, industrial motors and other electric equipment can in part replace fossil-fuel based counterparts in these sectors, reducing indirectly GHG emissions.

A well-established result from integrated assessment models (IAM) is that both *decarbonization* of electricity supply and *electrification* of the energy system play a decisive role in reaching climate stabilization (e.g., Luderer et al., 2012; Sugiyama, 2012; Williams et al., 2012; IEA, 2014; IPCC, 2014; Krey et al., 2014; McCollum et al., 2014; Sachs et al., 2014).[1] Indeed, stabilizing climate change to *any* level (e.g. 2, 3 or 4°C) requires reducing global emissions to near-zero levels (Collins et al., 2013; IPCC, 2013). Moreover, switching from fossil fuel to low-carbon electricity is one of the only technical options to drastically reduce GHG emissions in energy-intensive sectors such as industry, transportation and buildings.

Despite this consensus and its importance to inform the policy debate, cost-effective pathways of the future carbon content of electricity are not available to decision-makers, researchers in other disciplines, or the general public — in particular, none of the above-mentioned studies provides any pathway of the carbon content of electricity under climate stabilization targets. To fill this gap, we compute and report the carbon content of electricity in a set of existing prospective scenarios.

We focus on a set of 55 pathways generated with 10 different integrated assessment models (IAM) for the purpose of a recent IAM comparison study: AMPERE (Riahi et al., 2014).[2] IAMs compute cost-effective pathways of the socio-economic and energy systems under the constraint set by climate targets. They factor in a wide range of parameters, such as long-term demographic evolution; availability of natural resources; 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 (Wilson et al., 2013; Iyer et al.,

[1] These and other studies offer in-depth analysis of the interlinked dynamics of electrification and decarbonization of electricity, and cover topics out of the scope of this paper, such as economic implications and the role of different technologies to produce zero-carbon electricity.

[2] We chose this study as it is freely available online (IIASA, 2014), other recent studies such as EMF27 (Kriegler et al., 2014b) are of similar scope, use a broader variety of models and assumptions, and reach qualitatively and quantitatively similar results, but are unfortunately not publicly available online at the moment.

2014). IAMs are regularly peer-reviewed in comparison exercises (Clarke et al., 2009; van Vuuren et al., 2009; Edenhofer et al., 2010; Kriegler et al., 2014a,b) and occasionally evaluated against historical data (Guivarch et al., 2009; Wilson et al., 2013).

Unsurprisingly, the pathways of the carbon content of electricity from AMPERE confirm the above-mentioned consensus. Specifically, the pathways show that (1) near-zero-carbon electricity is necessary to reach concentrations consistent with global warming anywhere from 2°C to 3°C; (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 and should occur in every major country or region of the world.

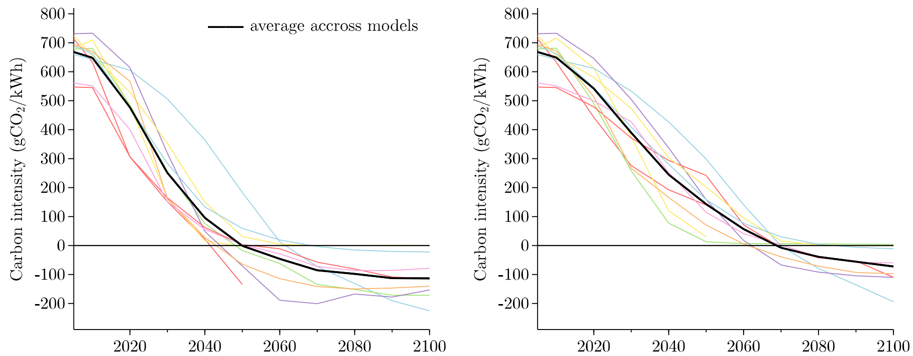
We report pathways at the global level and the country/region level for China, the EU, India and the US, under a variety of assumptions concerning the state of technology and long-term climate targets. These pathways may be useful to planners and policymakers designing climate mitigation strategies. First, they provide a reference on the speed at which decarbonization of the power sector should happen to meet a given climate target in a cost-effective way. They may thus be used to benchmark existing milestones, such as the ones proposed by the European Commission's energy roadmap (EC, 2011) and the Clean Power Plan currently under discussion in the US; or inform new measures in other countries or jurisdictions.

Second, such pathways of the carbon content of electricity are useful to assess the desirability of specific electrification technologies. Indeed, existing studies have focused on the impact of electrification on *today*'s GHG emissions, and concluded that it depends on the carbon intensity of power generation at the specific location where it takes place. For instance, electric vehicles may emit more GHG than conventional vehicles in countries where electricity is produced from coal (Sioshansi and Denholm, 2009; Hawkins et al., 2012a,b; Richardson, 2013).[3] However, since climate stabilization eventually requires near-zero carbon electricity, the relevant question for policymakers is not whether to electrify, but when to do it. The pathways reported make it possible to investigate this question, using what Hertwich et al. (2014) recently called an *integrated life cycle analysis*.[4]

The remainder of the paper is structured as follows. Section 1 reports pathways of the carbon content of electricity in the most technology-optimistic scenarios, where bio-energy combined with carbon capture and storage (CCS) al-

[3] Such studies have been interpreted as showing that electrification is to be avoided (e.g., BBC, 2012). Similar results have been reported by Thomson et al. (2000) on industrial electric furnaces, and Gustavsson and Joelsson (2010), Zabalza Bribián et al. (2009) and Ramesh et al. (2010) on buildings.

[4] As mentioned before, IAMs are sometimes used to assess optimal electrification of the economy. The pathways provided here can nonetheless be used by scholars outside the IAM community, for instance to evaluate the impact on GHG emissions of a technology or industrial process too specific to be explicitly represented in an IAM.




**(a)** 450 ppm — all carbon-free technologies **(b)** 550 ppm — all carbon-free technologies

**Figure 1:** Carbon content of electricity at the global scale in two scenarios: (a) stringent GHG concentration target (consistent with 2°C); (b) less stringent GHG concentration target (consistent with 3°C). Each thin line corresponds to the pathway simulated by one integrated assessment model (the reported carbon intensity for 2005 and 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.

lows for producing electricity with negative carbon emissions. Section 2 reports pathways in scenarios where either (i) both nuclear and CCS or (ii) renewable power are constrained. In both cases, the carbon content of electricity still decreases to near-zero levels. Section 3 and Appendix B detail pathways at the country/region level, for China, the EU, India and the US. They illustrate that the decrease to near-zero level can happen in every region of the world under a wide range of assumptions concerning technology availability, and is part of cost-effective strategies toward a range of different climate targets. Section 4 concludes.

## 1. Biomass combined with CCS could provide electricty with negative carbon content

During AMPERE, 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 1a 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 even fall below zero-carbon electricity. Indeed, this scenario assumes the technologies able to generate low-carbon electricity are widely available — these technologies include mainly wind, solar, hydro, biomass, nuclear and carbon capture and storage (Smith et al., 2009).

Among them, bio-energy with carbon capture and storage (BECCS), the burning of biomass in power plants associated to the long-term storage of resulting $CO_2$, allows to produce electricity with negative net GHG emissions (Tavoni and Socolow, 2013; Kriegler et al., 2014b).[5] When BECCS is available, the least-cost strategy to achieve global carbon neutrality is to produce negative-emission electricity and offset emissions from sectors of the economy that are more difficult to decarbonize.[6]

However, stabilizing GHG concentration around 450 ppm would require a fast intergovernmental coordination that may be difficult to achieve in time (Guivarch and Hallegatte, 2013; Stocker, 2013; Luderer et al., 2013). AMPERE considered the effect of a less stringent concentration target: 550 ppm $CO_2$-eq — generally admitted to be consistent with a 3°C warming, and still 15–51% probability of remaining below 2°C according to 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 1b).

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

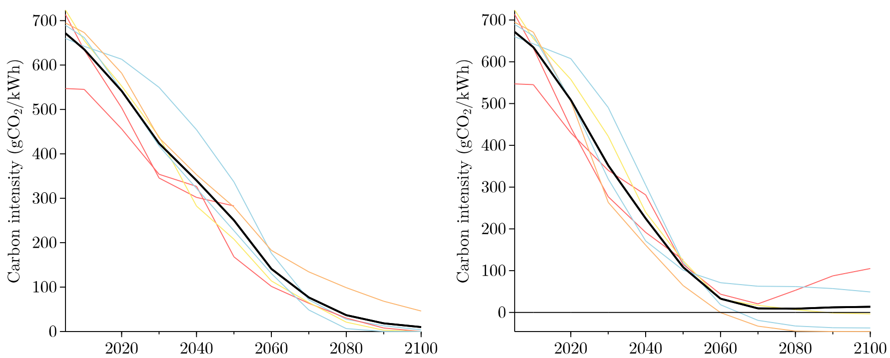
A third scenario in AMPERE sets a 550 ppm$CO_2$-eq stabilization target and assumes no further deployment of nuclear power after existing plants are decommissioned (for instance for social acceptability reasons) and assuming CCS never reaches market deployment. The decrease in carbon intensity of electricity holds under these assumptions (Figure 2a). The trajectories in this sample exhibit an average of more than 95% reduction in carbon intensity, reaching less than 25 g$CO_2$/kWh by 2100, while the most conservative pathway falls below 75 g$CO_2$/kWh.

Even in this scenario, decarbonization of power supply is sufficient to justify electrification. For instance, a conservative estimate of electric vehicles' (EV) consumption is 25 kWh/100km from the power plant to the wheel, that is accounting for losses when transmitting electricity over long distances and charging the battery.[7] In this case, electric vehicles, or hybrid vehicles running on electricity, would emit between 0 and 19 g$CO_2$/km by 2100. For comparison, the European target for new passenger vehicles sold in 2015 is 130 g$CO_2$/km on average, and the proposed objective for vehicles sold in 2021 is 95 g$CO_2$/km (ICCT, 2014).

[5] "Plants" extract carbon dioxide from the atmosphere as they grow.

[6] However, the large-scale feasibility and desirability of BECCs is controversial, given their potential impact on land use, food production, freshwater availability, and the uncertain availability of suitable geological storage sites — see Guivarch and Hallegatte (2013) for an overview.

[7] For instance, today's most sold electric car, the Nissan Leaf is rated between 18 and 21kWh/100km (battery to the wheel) by the US Environmental Protection Agency; and 20% is an accepted upper bound for transmission, distribution, and recharging losses.




**(a)** 550 ppm — No nuclear, no CCS

**(b)** 550 ppm — Low renewable

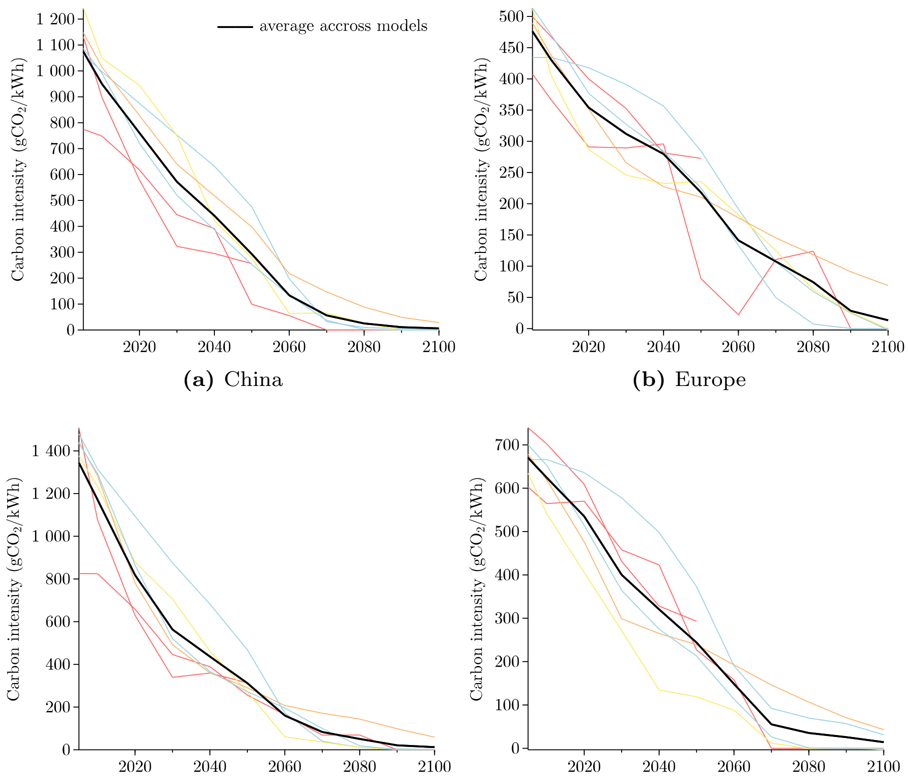
**Figure 2:** Decarbonization of global electricity in two 550 ppm scenarios (consistent with 3°C): (a) without new nuclear or carbon capture; (b) with low potential for renewable power. In both cases, the carbon content of electricity is reduced to near-zero levels by the end of the century.

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

## 3. Every major country or region of the world can and should decarbonize its electricity

Finally, according to AMPERE, the 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 less carbon-intensive. We consider the less favorable scenario both in terms of the concentration target (550 ppm) and in terms of technology availability (no replacement of nuclear capacities and no CCS allowed) — detailed pathways for these regions with different technology portfolios are displayed in the appendix (Figure B.4, Figure B.6, Figure B.7, and Figure B.5). In every region, the average carbon intensity decreases steadily during the 21st century, and falls below 100 gCO2/kWh in 2100 in every simulation.

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. For instance, indirect emissions from driving an electric vehicle would reach 100 $gCO_2$/km between 2030-2060 in China, 2010-2030 in Europe, 2030-2055 in India and 2020-2050 in the US; and would drop below 50 $gCO_2$/km between 2045-2065 in China, 2045-2060 in




**(a)** China

**(b)** Europe

**(c)** India

**(d)** USA

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

Europe, 2050-2070 in India and 2035-2060 in the US.

## 4. Conclusion

The work reported here has several limitations. We only analyzed scenarios where all countries participate in climate policies. In regions that do not participate or delay their participation in climate policies, the reduction in carbon intensity of power generation would not necessarily happen, or would be delayed (Kriegler et al., 2014a). Also, our analysis may overestimate the speed and/or potential of carbon intensity reduction in power generation. Indeed, IAMs may imperfectly represent real-world barriers that may hinder power generation decarbonization. Appendix A further discusses these limitations. Finally, the IAM comparison studied here does not investigate the consequences of simultaneous shortage of all the key low-carbon power generation technologies — CCS, nuclear, biomass and intermittent renewable.[8] In that case, stabilizing the climate would be made much more difficult, and would require a drastic reduction in global energy consumption.

The pathways towards clean electricity reported here should be interpreted cautiously. In particular, 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 very 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.

The pathways of the carbon content of electricity that we report can be used outside the community of integrated assessment, for instance when assessing the relevance of electric vehicles as a means to reduce greenhouse gas emissions; or to benchmark policies aiming at reducing carbon emissions from power plants. Further work could report pathways for other countries or regions of the world, and extend this approach to sectors other than power supply.

## References

BBC, 2012. Electric cars 'pose environmental threat'.
URL http://www.bbc.co.uk/news/business-19830232

Bibas, R., Méjean, A., 2014. Potential and limitations of bioenergy for low carbon transitions. Climatic Change 123 (3-4), 731–761.

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.

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.

EC, 2011. A roadmap for moving to a competitive low carbon economy in 2050. Communication from the Commission COM(2011) 112 final, European Commission.

Edenhofer, O., Knopf, B., Barker, T., Baumstark, L., Bellevrat, E., Chateau, B., Criqui, P., Isaac, M., Kitous, A., Kypreos, S., et al., 2010. The economics of low

[8] During AMPERE, IAMs explored the consequences of limited availability of renewable, limited availability of nuclear, and limited availability of CCS *separately* (as reported in Appendix B); in all these cases, the carbon intensity still decreases drastically in every region, sometimes to below-zero levels.

stabilization: model comparison of mitigation strategies and costs. The Energy Journal 31 (1), 11–48.

Guivarch, C., Hallegatte, S., 2013. 2C or not 2C? Global Environmental Change 23 (1), 179–192.

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 (11), 4259–4266.

Gustavsson, L., Joelsson, A., 2010. Life cycle primary energy analysis of residential buildings. Energy and Buildings 42 (2), 210–220.

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 (8), 997–1014.

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.

ICCT, 2014. Global passenger vehicle standards. International Council on Clean Transportation. theicct.org/info-tools/global-passenger-vehicle-standards.

IEA, 2012. $CO_2$ emissions from fuel combustion. IEA statistics, International Energy Agency.

IEA, 2014. Energy technology perspectives 2014: Harnessing electricity's potential. International Energy Agency and Organisation for Economic Co-operation and Development, Paris, France.

IIASA, 2014. AMPERE public database. International Institute for Applied Systems Analysis. secure.iiasa.ac.at/web-apps/ene/AMPEREDB.

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, cambridge university press Edition. [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.

IPCC, 2014. 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, cambridge university press Edition. [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.

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.

Krey, V., Luderer, G., Clarke, L., Kriegler, E., 2014. Getting from here to there – energy technology transformation pathways in the EMF27 scenarios. Climatic Change 123 (3-4), 369–382.

Kriegler, E., Riahi, K., Bauer, N., Schwanitz, V. J., Petermann, N., Bosetti, V., Marcucci, A., Otto, S., Paroussos, L., Rao, S., Curras, T. A., Ashina, S., Bollen, J., Eom, J., Hamdi-Cherif, M., Longden, T., Kitous, A., Méjean, A., Schaeffer, M., Wada, K., Capros, P., van Vuuren, D., Edenhofer, O., 2014a. Making or breaking climate targets: The AMPERE study on staged accession scenarios for climate policy. Technological Forecasting and Social Change (forthcoming).

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. v., 2014b. 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 (3-4), 353–367.

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 (1), 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 (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 (3-4), 651–664.

Meinshausen, M., Meinshausen, N., Hare, W., Raper, S. C., Frieler, K., Knutti, R., Frame, D. J., Allen, M. R., 2009. Greenhouse-gas emission targets for limiting global warming to 2°C. Nature 458 (7242), 1158–1162.

Ramesh, T., Prakash, R., Shukla, K., 2010. Life cycle energy analysis of buildings: An overview. Energy and Buildings 42 (10), 1592–1600.

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., 2014. 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 (forthcoming).

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.

Rose, S. K., Kriegler, E., Bibas, R., Calvin, K., Popp, A., Vuuren, D. P. v., Weyant, J., 2014. Bioenergy in energy transformation and climate management. Climatic Change 123 (3-4), 477–493.

Sachs, J., Tubiana, L., Guerin, E., Waisman, H., Mas, C., Colombier, M., Schmidt-Traub, G., 2014. Pathways to deep decarbonization. Interim 2014 report, Deep decarbonization pathways project (United nations' sustainable development solutions network and Institute for sustainable development and international relations), New York and Paris.

Sims, R. E., Rogner, H.-H., Gregory, K., 2003. Carbon emission and mitigation cost comparisons between fossil fuel, nuclear and renewable energy resources for electricity generation. Energy Policy 31 (13), 1315–1326.

Sioshansi, R., Denholm, P., 2009. Emissions impacts and benefits of plug-in hybrid electric vehicles and vehicle-to-grid services. Environmental Science & Technology 43 (4), 1199–1204.

Smith, H. J., Fahrenkamp-Uppenbrink, J., Coontz, R., 2009. Clearing the air - Introduction to the special issue on Carbon Capture and Sequestration. Science 325 (5948), 1641.

Stocker, T. F., 2013. The closing door of climate targets. Science 339 (6117), 280–282.

Sugiyama, M., 2012. Climate change mitigation and electrification. Energy Policy 44, 464–468.

Tavoni, M., Socolow, R., 2013. Modeling meets science and technology: an introduction to a special issue on negative emissions. Climatic Change 118 (1), 1–14.

Tavoni, M., Tol, R. S., 2010. Counting only the hits? the risk of underestimating the costs of stringent climate policy. Climatic change 100 (3-4), 769–778.

Thomson, M., Evenson, E., Kempe, M., Goodfellow, H., 2000. Control of greenhouse gas emissions from electric arc furnace steelmaking: evaluation methodology with case studies. Ironmaking & Steelmaking 27 (4), 273–279.

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 (12), 5125–5139.

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 (6064), 53–59.

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 (2), 381–395.

WRI, 2014. CAIT 2.0: WRI's climate data explorer. World Resources Institute. cait2.wri.org.

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 (12), 2510–2520.

## Appendix A. Methods

*Data*

We reanalyzed a set of 55 IAM pathways from AMPERE, a study for which $CO_2$ emissions for electricity are reported separately, thus allowing to recover the projected carbon intensity at each point (2005, 2010 and then every 10 years up to 2100).

We retain *final energy* as our measure of electricity production, that is, the total electric energy consumed by end-users, excluding that used by the power supply sector itself for transformation, transportation and distribution (including these losses would result in lower carbon intensities). As electricity-related emissions at a given point in time are readily available in our sample, computing cumulative emissions is straightforward.

## Limitations

The limitations in our analysis are of two kinds. First, we restricted our study to a subset of IAM trajectories by selecting only results reported in a recent model comparison study. This may introduce a selection bias. Second, IAMs may imperfectly represent real-life barriers to power generation decarbonization. We may therefore overestimate the speed and/or potential of power generation carbon intensity reductions.

*Bias*

We restricted our study to the results of a recent IAM comparison exercise, AMPERE, because the data are available online.

We are not aware of any published scenario that would reach a low or moderate atmospheric concentration target without featuring a decreasing carbon-intensity trajectory similar to the consensus highlighted here. However, reducing the study sample can always introduce biases. In particular, the studies presented here do not explore the case where all renewable energies, carbon capture and storage, nuclear and bio-energies turn out not to be widely available.

Moreover, 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). Our sample of trajectories may be affected by selection bias, given some models might not report their results with some generation technologies unavailable. When availability of some technologies is restricted, such as CCS and nuclear, the number of reported paths decreased, in particular when targeting 450 ppm $CO_2$-eq (this effect is mitigated with the looser

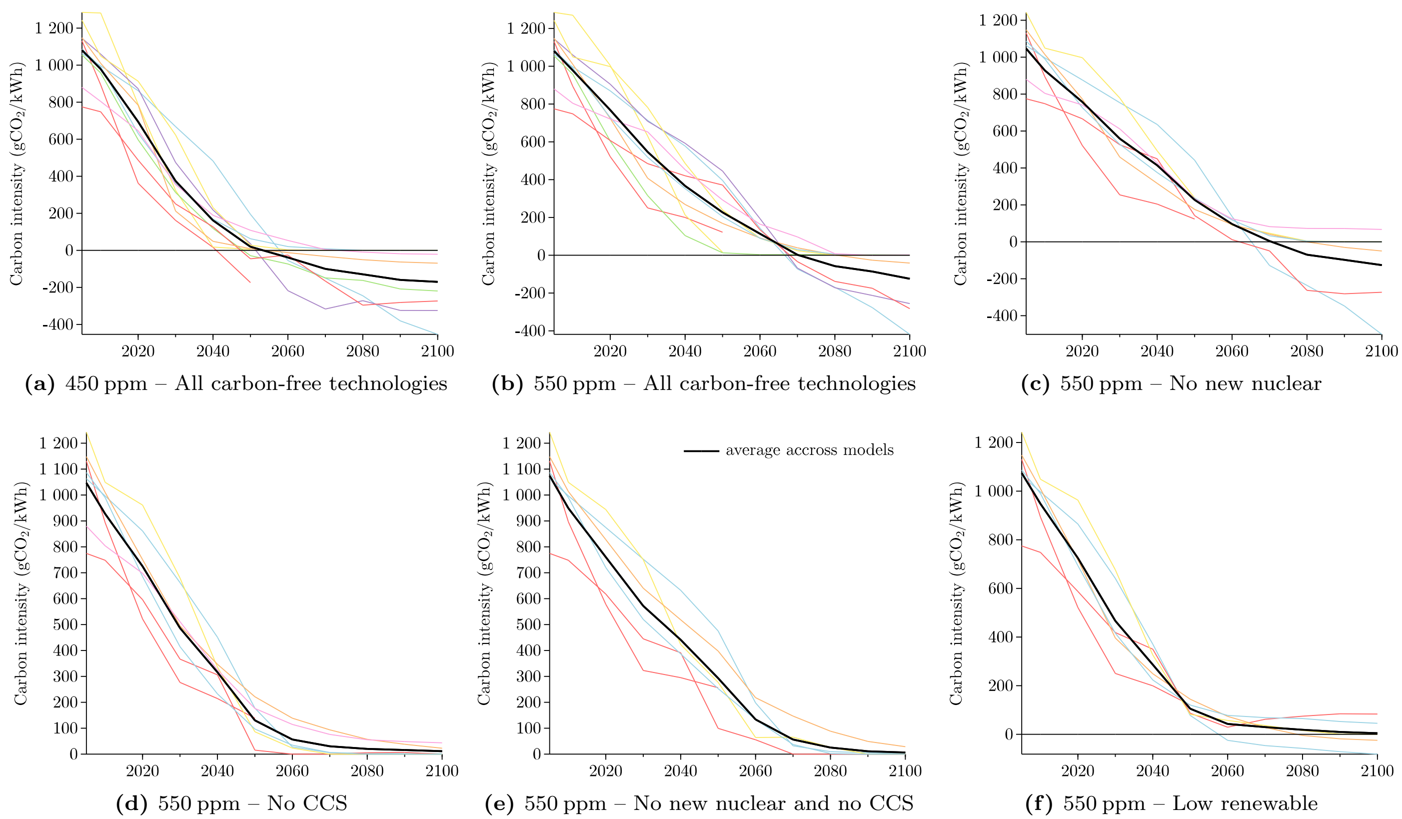
550 ppm $CO_2$-eq constraint).[9] This hints at the potential difficulty of reaching a stringent climatic target if the development of BECCS is constrained (Tavoni and Socolow, 2013; Bibas and Méjean, 2014; Rose et al., 2014).

*Barriers to the decarbonization of power generation*

IAMs might imperfectly account for several barriers to the decarbonization of power generation (Iyer et al., 2014). For instance, the capacity credit – the contribution of a given technology to meeting the demand – tends to be lower for intermittent renewable energy (mainly solar and wind) than for fossil fuel, nuclear, and bio-energy, due to potential mismatches between resource availability and demand peaks (Sims et al., 2003). Also, some low-carbon technologies may require to build 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).

## Appendix B. Additional figures

[9] 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.




**(a)** 450 ppm – All carbon-free technologies

**(b)** 550 ppm – All carbon-free technologies

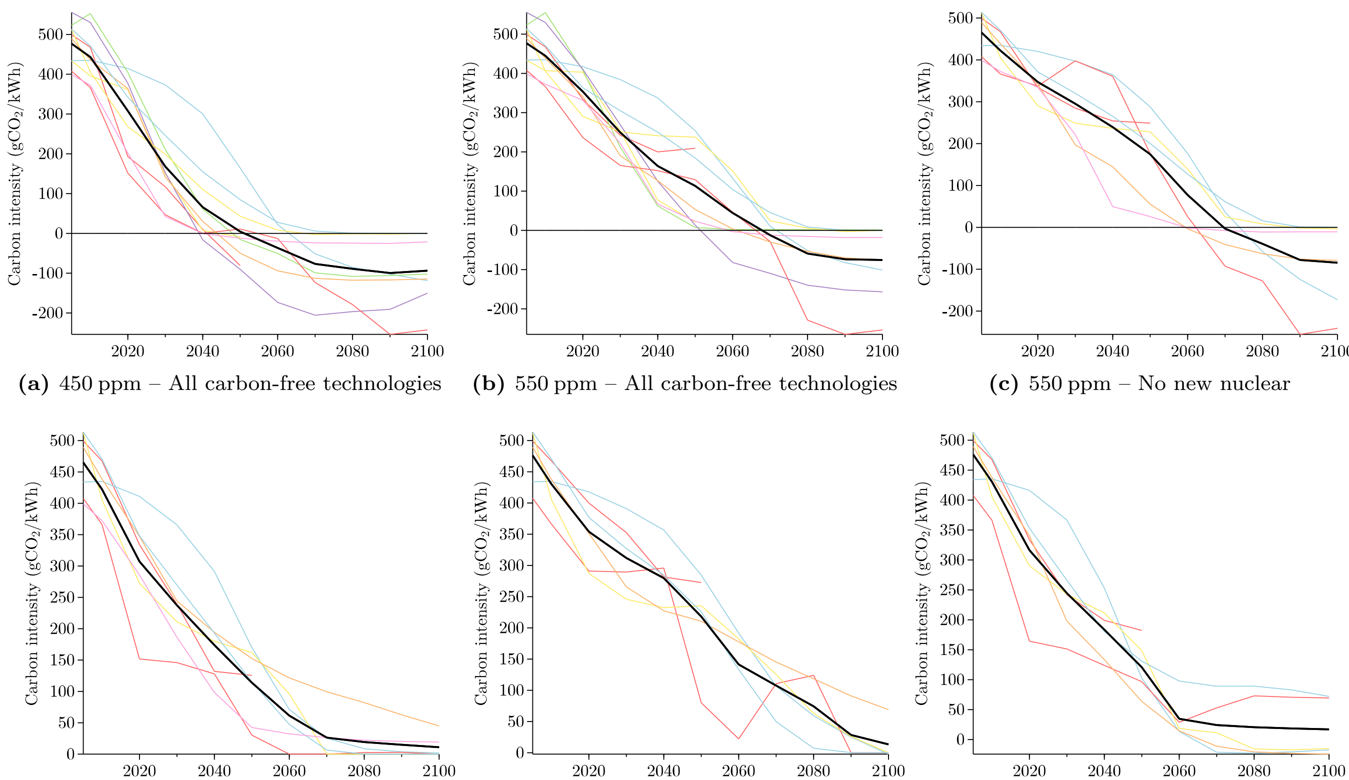
**(c)** 550 ppm – No new nuclear

**(d)** 550 ppm – No CCS

**(e)** 550 ppm – No new nuclear and no CCS

**(f)** 550 ppm – Low renewable

**Figure B.4:** Carbon content of electricity in China.




**(a)** 450 ppm – All carbon-free technologies

**(b)** 550 ppm – All carbon-free technologies

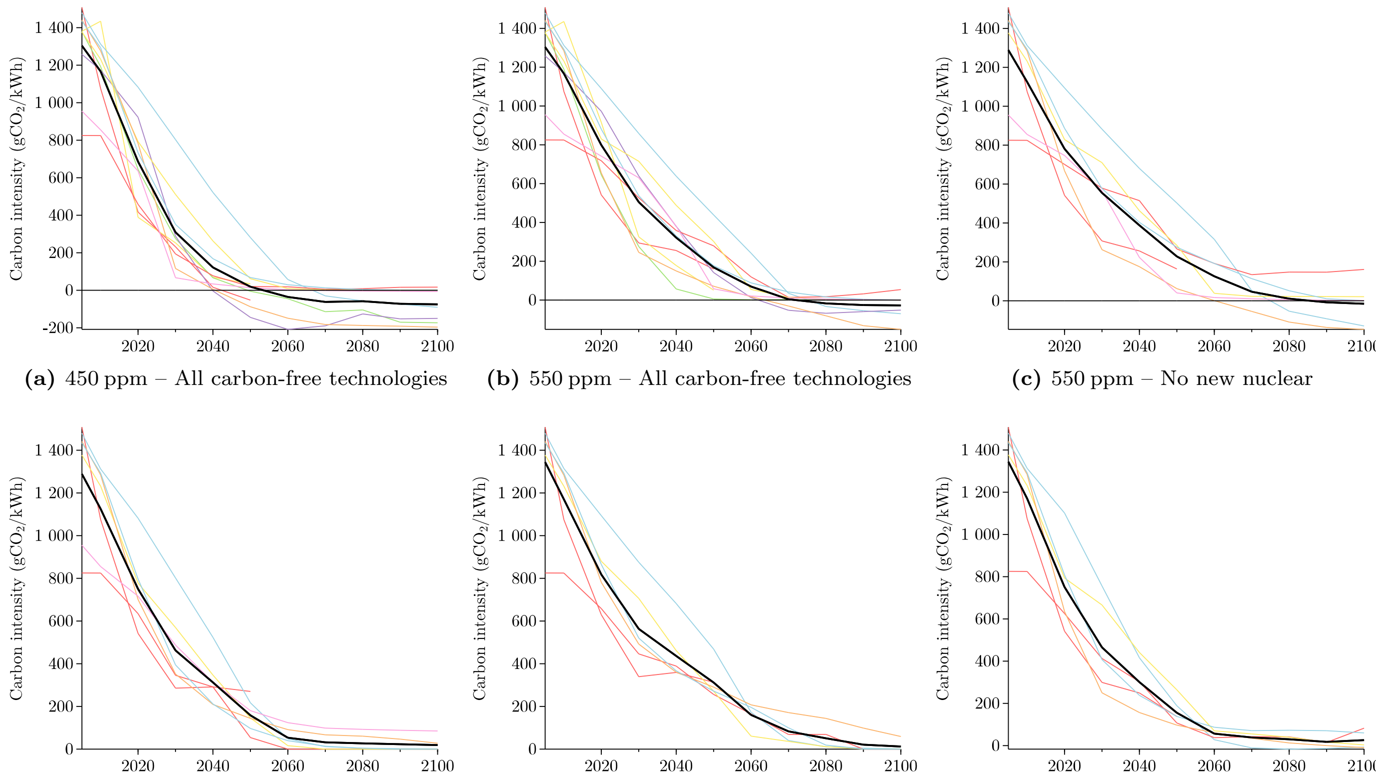
**(c)** 550 ppm – No new nuclear

**(d)** 550 ppm – No CCS

**(e)** 550 ppm – No new nuclear and no CCS

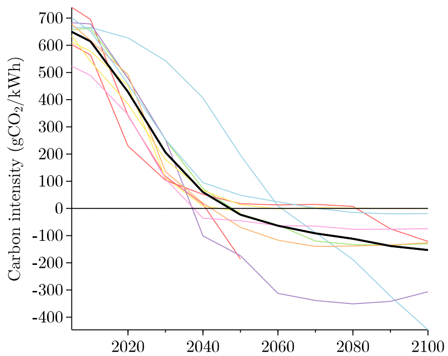
**(f)** 550 ppm – Low renewable

**Figure B.5:** Carbon content of electricity in the EU.

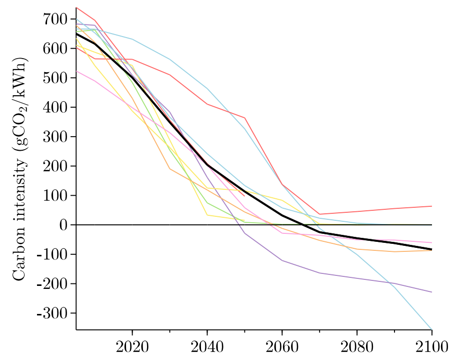



**(a)** 450 ppm – All carbon-free technologies
**(b)** 550 ppm – All carbon-free technologies
**(c)** 550 ppm – No new nuclear
**(d)** 550 ppm – No CCS
**(e)** 550 ppm – No new nuclear and no CCS
**(f)** 550 ppm – Low renewable

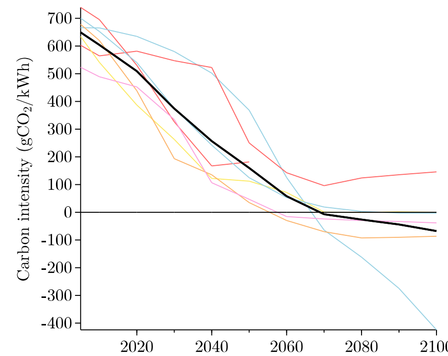
**Figure B.6:** Carbon content of electricity in India.



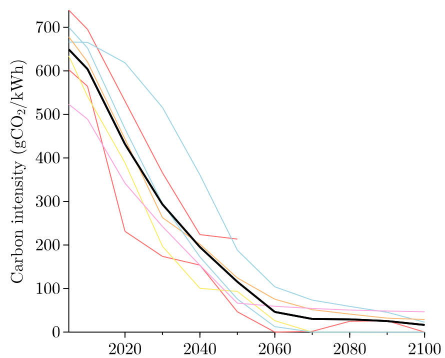

**(a)** 450 ppm – All carbon-free technologies



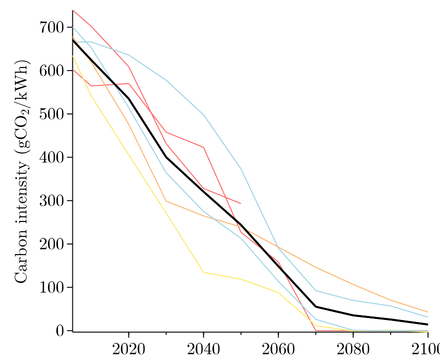

**(b)** 550 ppm – All carbon-free technologies



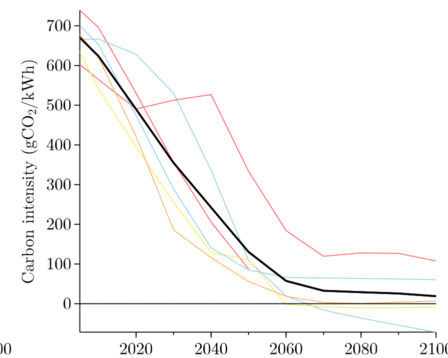

**(c)** 550 ppm – No new nuclear




**(d)** 550 ppm – No CCS

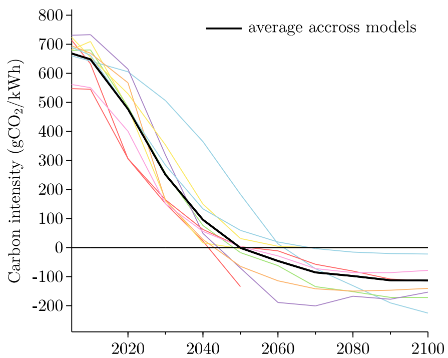



**(e)** 550 ppm – No new nuclear and no CCS

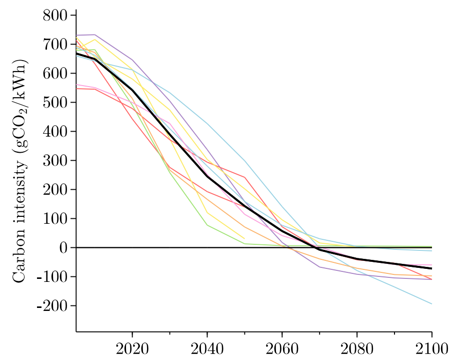



**(f)** 550 ppm – Low renewable

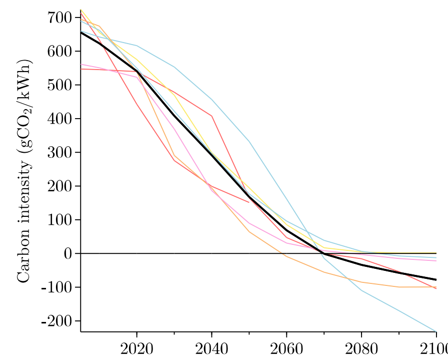
**Figure B.7:** Carbon content of electricity in the US.



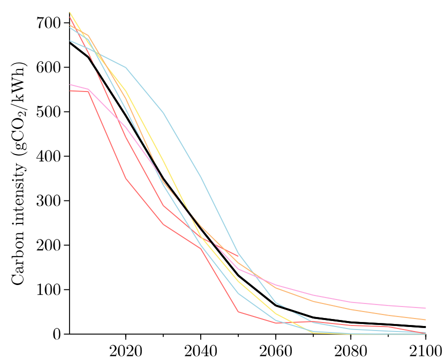

**(a)** 450 ppm – All carbon-free technologies



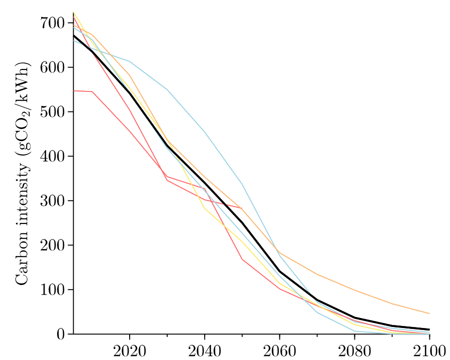

**(b)** 550 ppm – All carbon-free technologies



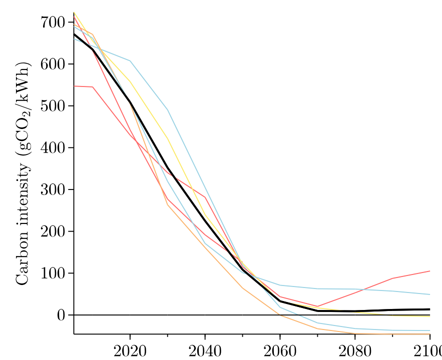

**(c)** 550 ppm – No new nuclear




**(d)** 550 ppm – No CCS




**(e)** 550 ppm – No new nuclear and no CCS




**(f)** 550 ppm – Low renewable

**Figure B.8:** Carbon intensity of electricity at the global level.