Common but Differentiated Leadership: Strategies and Challenges for Carbon Neutrality by 2050 across Industrialized Economies

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Abstract

Given their historic emissions and economic capability, we analyze a leadership role for representative industrialized regions (EU, US, Japan, and Australia) in the global climate mitigation effort. Using the global integrated assessment model REMIND, we systematically compare region-specific mitigation strategies and challenges of reaching domestic net-zero carbon emissions in 2050. Embarking from different emission profiles and trends, we find that all of the regions have technological options and mitigation strategies to reach carbon neutrality by 2050. Regional characteristics are mostly related to different land availability, population density and population trends: While Japan is resource limited with respect to onshore wind and solar power and has constrained options for carbon dioxide removal (CDR), their declining population significantly decreases future energy demand. In contrast, Australia and the US benefit from abundant renewable resources, but face challenges to curb industry and transport emissions given increasing populations and high per-capita energy use. In the EU, lack of social acceptance or EU-wide cooperation might endanger the ongoing transition to a renewable-based power system. CDR technologies are necessary for all regions, as residual emissions cannot be fully avoided by 2050. For Australia and the US, in particular, CDR could reduce the required transition pace, depth and costs. At the same time, this creates the risk of a carbon lock-in, if decarbonization ambition is scaled down in anticipation of CDR technologies that fail to deliver. Our results suggest that industrialized economies can benefit from cooperation based on common themes and complementary strengths. This may include trade

of electricity-based fuels and materials as well as the exchange of regional experience on technology scale-up and policy implementation.

Introduction

With the Paris Agreement, 195 signatory states commit to achieve the goal of limiting global warming to 1.5-2°C under the principle of "common but differentiated responsibilities" (UNFCCC, 2015). This refers, in particular, to the responsibility of industrialized countries who reached economic prosperity and contributed significantly to historic emissions.

The total carbon budget for climate stabilization at 1.5-2°C is estimated to be 2,900-3,600 Gt CO2 of which 2,300 Gt CO2 have already been emitted (IPCC, 2018). The US and the EU28 alone contributed more than a third of cumulative historic emissions (*Suppl. Fig. 1)*. Acknowledging that current generations benefit from a history of fossil-fueled development, the role of industrialized countries becomes even more significant. Dividing historic emissions by current population, the US, Canada, Australia, the EU, Russia and Japan stand out, while the rest of the world is responsible only for minor contributions on a per-capita basis (Fig. 1a).

Limiting global warming to 2°C requires global carbon neutrality by 2070, while a 1.5°C target requires global carbon neutrality by 2050 (IPCC, 2018). Global modeling scenarios usually apply uniform carbon pricing which leads to cost-optimal abatement across regions. However, under a 2°C scenario, this approach still generates a significant gap in domestic per-capita emissions by 2050 between industrialized countries and the rest of the world (Fig. 1b). In the absence of burden-sharing mechanisms, this conflicts with standards of global equity as convergence of domestic per-capita emissions is postponed. Carbon neutrality by 2050 can serve as a sensible focal point for industrialized economies in the Paris context of 1.5°C to 2°C stabilization that is aware of global disparities.

Our study explicitly investigates mitigation strategies and challenges to reach domestic net-zero CO2 emissions by 2050 in four representative industrialized economies: Australia, the US, Japan and the EU28. Industrialized economies take leadership roles abating emissions earlier and deeper by mid-century compared to both i) the rest of the world and ii) their emissions trajectories in uniform carbon pricing scenarios (Fig. 1b).

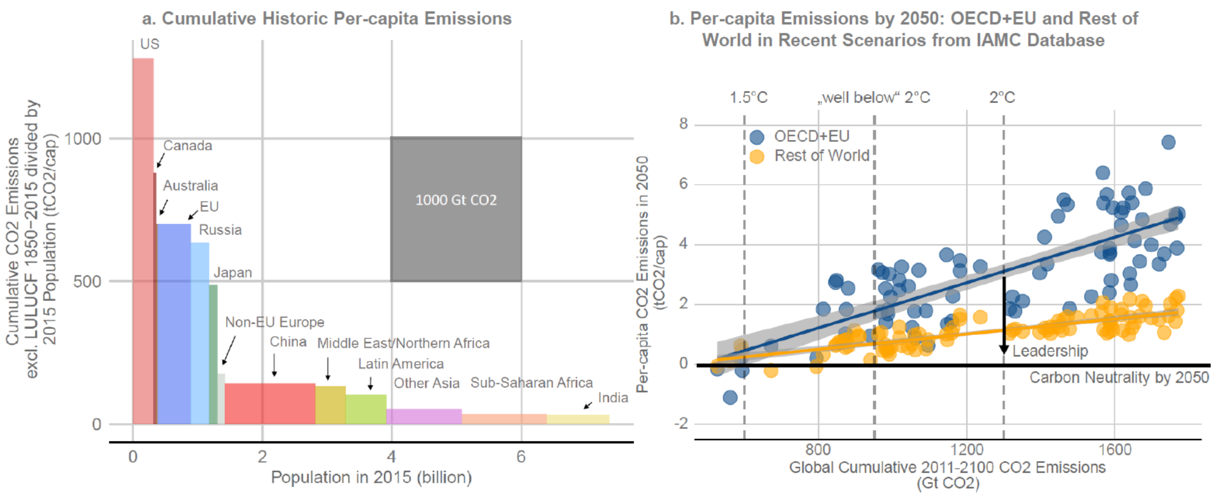


Figure 1, ***left panel (a)****: World regions ordered by cumulative historic carbon emissions between 1850 and 2015 (excluding emissions from land-use change) divided by population (y-axis). The x-axes shows population in 2015. Historic emission data are from Gütschow et al. (2016, 2017, 2019).* ***Right panel (b):*** *Per-capita net CO2 emissions by 2050 in EU+OECD countries (blue dots) and the Rest of World (yellow dots) against global cumulative 2010-2100 CO2 emissions in selected scenarios from the EMF33, CD-Links and ADVANCE integrated assessment modeling intercomparison projects (Huppmann et al., 2018, for details on selected scenario see Suppl. S18). Global 2011-2100 CO2 budgets of 600/900/1300 Gt CO2 represent 1.5°C/"well below" 2°C/2°C scenarios respectively (Table*

2.2 in IPCC (2018), column 67% probability, subtract about 100 Gt CO2 for end-of-century budget to account for Earth System feedbacks and add 290 GtCO2 for 2011-2018 emissions).

On the federal level, current climate policy signals towards 2050 targets differ across the four industrialized economies. As of July 2020, the EU, Japan and the US have submitted Midcentury-Strategies (MCS) to the UNFCCC to outline their mitigation ambition towards 2050 in respect of the Paris long-term goals. Driven by recently proposed European Green Deal, the European MCS aims at net-zero greenhouse gas (GHG) emissions by 2050 (EU, 2020; EU Commission, 2018). Japan has been more cautious about its long-term commitments given its history of energy import dependence and the Fukushima accident. The Japanese Government (2019) submitted an MCS with a 2050 target of 80% GHG reductions, albeit without specifying a base year. On the federal level, Australia and the US lack ambitious climate policies or long-term targets (Climate Action Tracker, 2019) and Australia has not submitted a MCS so far. The US MCS by the Obama Administration considered pathways for an 80% GHG reduction to 2005, yet the current government plans to withdraw from the Paris Agreement completely.

Despite mixed signals from the governments in office, we observe that the national and state-level climate policy discourse in the industrialized economies increasingly leans towards the idea of a net-zero CO2 or even net-zero greenhouse gas (GHG) emissions target by 2050. The latter is more ambitious, yet the distinction between CO2 and GHG targets is in the policy discourse not always clear. All Australian states have a net-zero (CO2 or GHG) target by 2050 or earlier and the recent unprecedented scale of bushfires has raised public awareness about climate change (Hope, 2020; Mazengarb, 2020). In the US, parts of the Democratic Party proposed the Green New Deal, an ambitious climate policy program with a net-zero GHG target for 2050 (Ocasio-Cortez, 2019). Several states including California declared the intention to go net-zero (CO2 or GHG) by midcentury (Podesta et al., 2019). In Japan, too, a number of subnational actors, including the Tokyo Metropolitan government, proclaim net-zero CO2 targets for 2050 (MOE Japan, 2020; Tokyo Metropolitan Government, 2019). Although current mitigation efforts of industrialized economies are insufficient to reach Paris-compatible long-term goals (den Elzen et al., 2019; Rogelj et al., 2016), carbon or greenhouse gas neutrality by 2050 has become a focal point for ambitious national actors.

For our analysis, we focus on domestic carbon neutrality in 2050 for four selected regions that represent a range of industrialized economies. With respect to the differing characteristics (e.g. land availability and energy demand profile), we ask how their transformation pathways compare. We focus on the energy system and do not analyze abatement of non-CO2 GHGs such as CH4 and N2O in agriculture and industry. Specifically, we carve out regional mitigation strategies and challenges across three dimensions of a net-zero transformation: electricity decarbonization, energy demand-side decarbonization and carbon dioxide removal (CDR) options. While electricity decarbonization is the key-step of the supply-side transformation, it needs to be complemented by a demand-side transformation across sectors (buildings, industry, transport). Finally, CDR options can serve to compensate for any residual carbon emissions.

There is a myriad of national modeling studies to analyze economy-wide mitigation pathways up to 2050 in one of the four regions and we only mention a few here. For Australia, ClimateWorks et al. (2014) provide an illustrative scenario for net-zero GHG emissions in Australia by 2050, analyzing detailed sectoral transitions and CDR options with a suite of harmonized modeling tools and bottom-up assessments. In addition to the MCS study (ref), Lempert et al. (2019) present 80% GHG reduction pathways to 2050 for the US economy based on the GCAM-USA model. Moreover, there are several bottom-up energy system studies with a focus on renewable electricity (e.g. Jacobson et al., 2015; Steinberg et al., 2017). A rich national literature on integrated assessment exists for Japan (e.g. Oshiro et al., 2018, 2019; Kato & Kurosawa, 2019; Sugiyama et al., 2019). They find significant challenges for reaching net-zero carbon by 2050 (Oshiro et al., 2018) and highlight the importance of industry (relative to transport) decarbonization in Japan (Sugiyama et al., 2019). Next to the MCS study (EU Commission, 2018), there are further EU-focused integrated assessment analyses based on the PRIMES framework (Fragkos et al., 2017; Vrontisi et al., 2019). They come with significant technological detail and focus on the aggregate GDP cost of the transformation. Finally, the Deep Decarbonization Pathways Projects (DDPP) provides a comprehensive collection of national modeling studies (incl. US, Australia, Japan) under a harmonized framework (Bataille et al., 2016).

This study takes a different perspective by providing a cross-regional comparison of transformation pathways for net-zero CO2 using a global integrated assessment model (IAM). It has the advantage of treating all regions within one consistent modeling framework, yet it cannot provide the regional detail of dedicated national models. Previous IAM studies focus on a broader set of regions and investigate scenarios with a globally harmonized carbon price (Marcucci & Fragkos, 2015; Tavoni et al., 2014; Van Sluisveld et al., 2013; van Soest et al., 2017). Here, we concentrate on four regions and analyze scenarios with domestic regional net-zero carbon targets for 2050, which are not globally cost-optimal yet more meaningful to national and international policy debates. A challenge to our single-model study is that IAMs can have different approaches to represent the complex energy-economy dynamics and are subject to structural uncertainty. This is why the IAM literature usually conducts multi-model studies to increase the robustness of model results. Notwithstanding, we see our single-model perspective as an opportunity to discuss and explain our results in detail and provide a deeper insight into the underlying mechanisms, which would be more difficult to disentangle from methodological differences in a multi-model picture.After presenting scenarios and modeling framework (section 2), we provide an overview of the regional pathways (section 3.1). We then dive into cross-regional comparisons of electricity decarbonization (section 3.2), energy demand-side decarbonization (section 3.3) and carbon dioxide removal options (section 3.4) and summarize our conclusions (section 4).

Methods

We analyze scenarios using the Integrated Assessment modeling framework REMIND that models pathways of a coupled energy-economy system subject to climate targets (Kriegler et al., 2017; Luderer et al., 2015). We use a regionally-adapted version of REMIND 2.1.2 (Luderer et al., 2020) with 13 world regions, among them, the European Union, and six individual countries (China, India, Japan, United States of America, Russia and Australia). Each region optimizes intertemporal welfare based on a Ramsey-type macro-economic growth model and is subject to a budget constraint including consumption, capital investment, primary energy trade and energy system cost. REMIND brings together the capacities of bottom-up and top-down approaches by linking the macroeconomic production function to a technology-rich energy system model (see Suppl. S2 for details on the model).

We analyze a suite of scenarios with a net-zero CO2 emissions target for the EU, Australia, Japan and the US and a common carbon price for the remaining regions (Table 1). The model adjusts regional carbon prices iteratively until the regional and global emission targets are met (Suppl. S3). The carbon price of the industrialized economies is determined by the 2050 net-zero target, while for the remaining regions it is determined such that a 2011-2100 global carbon budget of 1300 GtCO2 is respected. To contrast regional properties and dependences of net-zero pathways, we run a number of sensitivity scenarios on electricity technology and carbon dioxide removal (CDR) deployment.

<table>
<tr><th>Scenario</th><th>Climate target</th><th>Regional sensitivities
(applied to Australia, US, EU, Japan)</th></tr>
<tr><td>Current Policies
(Reference Scenario)</td><td>● Low carbon price trajectories reflecting current policies (see Suppl. S4)</td><td></td></tr>
<tr><td>Net-zero (standard full-option)</td><td rowspan="6">● Australia, US, EU, Japan: net-zero CO2 emissions by 2050
● remaining regions: carbon price in line with global 2011-2100 carbon budget of 1300 Gt CO2</td><td></td></tr>
<tr><td>Net-zero Nuc. out</td><td>● phase-out of all nuclear power capacity by 2040</td></tr>
<tr><td>Net-zero Nuc. out + low VRE Pot.</td><td>● phase-out of all nuclear power capacity by 2040
● limit variable renewable (VRE) generation (onshore wind, solar CSP, solar PV) to 5% in all grades of resource quality that have not been used by 2020
● this is to obtain an order of magnitude small VRE potential for newly built plants in the case of increased land-use competition and lack of public acceptance</td></tr>
<tr><td>Net-zero No Land-Use CDR</td><td>● no negative land-use change emissions allowed</td></tr>
<tr><td>Net-zero No Land-Use + CCS CDR 15%</td><td>● negative emissions only come from BECCS and DACCS and are limited to 15% relative to 2020 emissions
● this is to see the effect of forcing a high level (85%) of gross emission reductions across all regions (90% is not feasible for all regions in our model)</td></tr>
</table>

Table 1: Overview of scenarios analyzed in our study.

Results and Discussion

Overview

To summarize similarities and differences of our net-zero scenario across the four industrialized economies, Figure 2 provides an overview of current emissions and the respective pathways to carbon neutrality by 2050. It shows an emission decomposition across sectors (emissions bars, Fig. 2b) and abatement contributions between the reference scenario (*Current Policies*) and the *Net-zero* scenario of different mitigation strategies (colored areas between thick and dashed line, Fig. 2a).

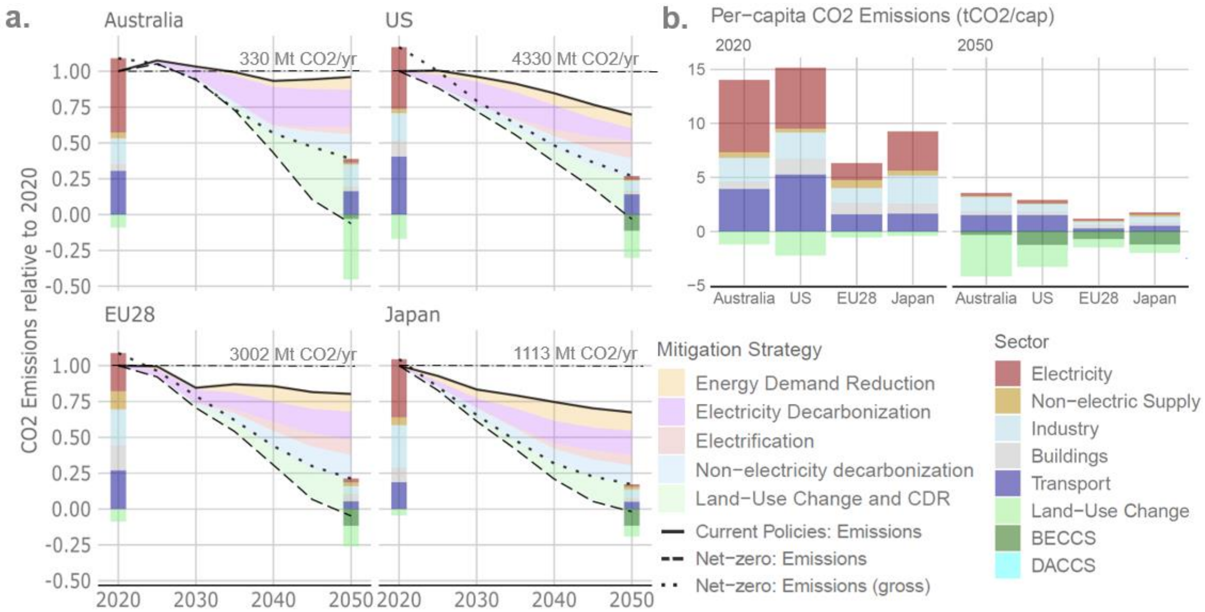


Figure 2: Overview of net-zero decarbonization pathways for the four industrialized economies in REMIND. ***Left panel (a):*** *Net CO2 Emissions relative to (modeled) 2020 levels in reference (Current Policies) scenario (black line) and the Net-zero scenario (dashed line). The dotted line represents gross emissions in the Net-zero scenario. Bars show the sectoral composition of CO2 emissions in 2020 and 2050 respectively. The emission abatement between the reference scenario and Net-zero scenario is attributed to different mitigation strategies (see Suppl. S17 for decomposition method). The reference 2020 emissions can be seen in absolute numbers above the vertical line of the 2020 level.* ***Right panel (b):*** *Per-capita CO2 emissions per sector in 2020 and 2050.*

We find that all of the four regions have technological options and mitigation strategies to reach net-zero carbon emissions by 2050, although they embark from historically different emissions profiles and trends. The point of departure for the low-carbon transformation differs across the four regions mainly for two reasons.

First, regional characteristics such as population density, geography and historic developments in energy and industry infrastructure shape regional energy demand structures. Current per-capita CO2 emissions in Australia and the US are almost double the levels of the EU and Japan (Fig. 2b). The main reason is their high per-capita energy demand in the transport, industry, and (in the case of the US) buildings sector. The European and especially the Japanese economy have historically been less energy intensive (per unit of GDP) than the Australian and the US American economy and still are today (Suppl. Fig. 4 Schandl & West, 2012; Warr et al., 2010). In Japan, this is the result of a history of energy dependence, limited resources and high energy prices (Steward, 2009).

Second, the four regions are at different stages of a transition to low-carbon electricity (Fig. 3a). Australia still generates about 60% of its electricity from coal and started renewable expansion only recently (Ueckerdt et al., 2019). The EU, in contrast, has experienced a partial shift from coal to gas and nuclear power in the late 20th century and, over the past two decades, a significant growth of renewables to about 30% of total electricity generation. The US cut its electricity emissions over the past years by rapidly replacing coal with gas power, while Japan's power sector is on an upward emissions trend since the Fukushima accident seeing nuclear power replaced by coal and gas (Fig 3a, *Suppl. Fig. 5).*

Emissions decrease across all regions in the *Current Policies* scenario and, most notably, in the US and Japan (Fig. 2a). This is driven mainly by the US phase-out of coal electricity (Fig. 3a) and declining populations in Japan (Suppl. Fig. 13). Relative to the *Current Policies* scenario, electricity decarbonization in the *Net-zero* scenario contributes about one third of total gross abatement. Respective contributions are even larger in Australia due to its continued reliance on cheap coal electricity under *Current Policies* (Fig. 3b). Remaining gross reductions come from energy efficiency improvements, the increase of the electricity share in final energy (electrification) and non-electricity decarbonization. The latter includes a switch to low-carbon fuels (biofuels, hydrogen) on the demand-side and reducing emissions from district heating and refineries (non-electric supply emissions).

In the standard *Net-zero* scenario, residual emissions from the demand-side sectors (buildings, industry, transport) remain by 2050 and are compensated by CDR. Those emissions occur on site of energy use, such as from combustion in vehicle engines or industrial boilers excluding upstream emissions from energy production. We confirm earlier global modeling findings that it is cost-efficient to only partially decarbonize non-electric energy by 2050 and use CDR options for compensation (Bauer et al., 2018; Luderer et al., 2018; Strefler et al., 2018; IPCC, 2018). However, we find that the optimal trade-off level between gross and CDR abatement is region-specific due to differences in a) CDR potentials and b) non-electric decarbonization challenges. While Australia compensates for residual fossil emissions of about 40% relative to 2020 through CDR (4 tCO2/cap), in Japan, CDR compensates for about 15% (1.5 tCO2/cap, Fig 2a, Suppl. Fig. 10).

Electricity Decarbonization:

In the *Net-zero* scenario, electricity generation is completely decarbonized in 2040 by scaling up (onshore) wind and solar PV generation to shares of up to 80% in the power mix (Fig. 3a, Suppl. Fig. 10). An exception is Japan where limited potentials of variable renewables (VREs) lead to a wind and solar share of only 50% that is complemented by the deployment of nuclear and biomass technologies (see Suppl. S10 for assumptions on nuclear power in Japan). If nuclear power is not available in Japan or, in addition, VRE potentials are more limited, the model chooses biomass and fossil CCS technologies to fill the resulting gap (Fig. 3b).

The dominance of wind and solar technologies is driven by several factors: First, steep recent cost reductions have made current new onshore wind and solar PV plants (at low VRE shares) competitive with fossil generation (IRENA, 2019). Assuming learning-by-doing, the downward trend of wind and solar generation cost continues in our scenarios. Second, integration challenges concerning high VRE shares are manageable, both technologically and economically and refined power sector representations in IAMs tend to show low integration cost (see Suppl. S7 for details). With the exception of Japan, this also leads to significant 2050 VRE shares in our *Current Policies* scenario.

In the 2020s and 2030s, the average specific cost of electricity increase across all four regions, while by 2050 they return to levels similar to today (Fig. 3a, white dots scaled on right axis). High cost of electricity in the transition period are due to the rapid scale-up of VREs, storage and transmission, complementing early retirement of coal and gas generators. Transition cost are particularly high in Japan due to higher VRE capital costs in line with current trends (IRENA, 2019; Mizuno, 2014) and low capacity factors.

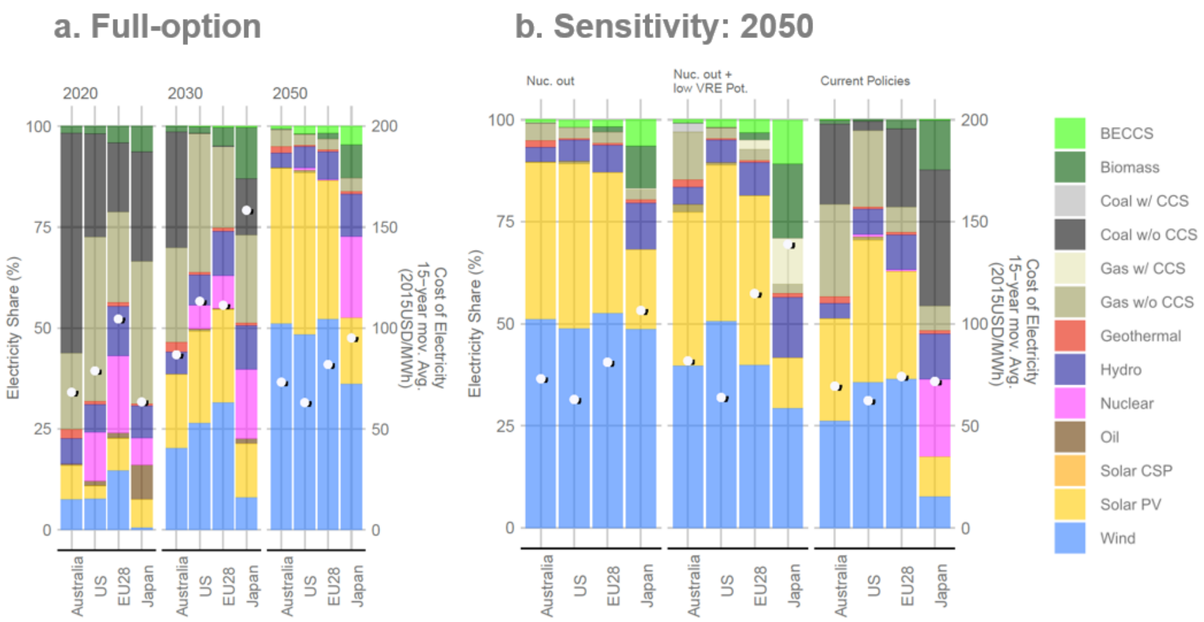


*Figure 3: **Left panel (a):** Electricity mix in 2020, 2030 and 2050 in Net-zero scenario (bars, left y-axis) and 15-year moving average cost of electricity (white dots, right y-axis). **Right panel (b):** Electricity mixes (bars) and cost of electricity (white dots) for 2050 across different scenarios: net-zero scenario with regional nuclear phase-out by 2040 (left), net-zero scenario with nuclear phase-out and limited wind and solar potentials (center) and Current Policies scenario (right).*

Average 2050 cost of electricity in the *Net-zero* scenario are only slightly lower in Australia and the US relative to Japan and the EU (Fig. 3b). In the case of Japan however, a nuclear phase out by 2040 increases cost of electricity. If, in addition, only a fraction of the VRE potential is accessible due to social concerns regarding land availability and grid expansion both, Japan and the EU, face higher cost of electricity than Australia and the US who have access to large VRE resources (Fig. 3b, Suppl. Fig. 13). Aggregate cost metrics like GDP losses and energy system cost are relatively insensitive to these power sector constraints, yet given limitations of sector coupling in our model we are likely to underestimate those cost effects in an economy-wide picture (see Suppl. S8 for discussion).

Our regional differences in average cost of electricity are driven by generation cost (investment cost, capacity factors, fuel cost, see Suppl. S11 for details). If VRE capacity factors are low or VRE potentials limited such that other low-carbon technologies are required, the cost of electricity increase. Our model only includes a simple regional differentiation of aggregated integration costs which does not reflect regional heterogeneities in network layout or matching between temporal profiles for demand and supply. In general, large VRE-based power grids as in Australia benefit from more balanced VRE supply profiles as they integrate regions with differing weather patterns, while simultaneously requiring more transmission infrastructure.

Our results suggest that regional differences in low-carbon electricity cost depend significantly on the social acceptability of nuclear power or VRE expansion. In Japan, nuclear power policy has to navigate between public opposition, corporate lobbies and concerns about (low-carbon) energy security (Vivoda, 2012). The recent example of the slowdown of wind energy deployment in Germany shows the vulnerability of VRE expansion in densely populated parts of Europe as public resistance against new wind parks or transmission lines forms (Kędzierski, 2019). Underground transmission lines can promote social acceptability but increase the cost of VRE expansion. Although there have been attempts to assess socially acceptable VRE potentials (Harper et al., 2019), the effectively realizable VRE potential remains a key uncertainty for densely populated regions like Japan and parts of the EU such as Germany or the Netherlands.

Demand-Side Transformation

Final energy consumption declines in the *Net-zero* scenario across all regions. However, Japan almost halves energy use by 2050 relative to 2020, while Australia hardly reduces energy consumption by 2050 (Suppl. Fig. 14). This is driven by population trends and per-capita energy demand patterns. While Australia and the US face high per-capita demands and increasing populations, Japan and the EU use less energy per-capita and expect declining populations (Suppl. Fig. 13 and 15).

Reaching net-zero carbon by 2050 requires substantial cuts in direct emissions from the buildings, industry and transport sector. Figure 4 summarizes indicators for the main options of the model to reduce demand-side emissions by energy demand reduction, electrification or the use of biofuels. As electricity and bioenergy shares increase rather homogenously across regions, persisting high per-capita energy demand in Australia and the US translates into high per-capita demand-side emissions by 2050. The EU and Japan show slightly higher electricity shares in transport driven by our assumption of high (non-carbon) taxes on transport fuels that promote a shift to electrification. However, the model does not consider regionally different structures of energy service demand within the sectors, which may well outweigh this effect (e.g. Australia has a large aluminum sector, which is less challenging to electrify than the significant Japanese steel sector, JISF, 2019; Madeddu et al., under review). Australia uses less transport biofuels as they are competitive mostly in combination with carbon capture and storage, which Australia does not need due to large CDR potentials from land-use change.

Current per-capita energy use in Australia and the US is almost double relative to Japan and the EU across the three sectors (Suppl. Fig. 15). Besides regional differences in energy efficiency (Honma & Hu, 2014; Warr et al., 2010), this is driven by different energy demand structures due to infrastructural, cultural and geographic factors, which will likely remain. This is most relevant in transport. Australia and the US are more dependent on road transport and have limited public bus and rail infrastructure (Buehler, 2011; Lipscy & Schipper, 2013). Moreover, they have a higher per-capita demand for domestic aviation and freight transport (Suppl. Fig. 15). Given these structural differences in energy demand, we chose modeling assumptions such that the gap in per-capita final energy use between the regions decreases but does not fully close.

As with other integrated assessment models, our model sees lower electrification potentials than indicated by bottom-up studies (Lechtenböhmer et al., 2016; Madeddu et al., under review). This is because of the way we represent electrification in a macroeconomic production function which tends to reproduce historic fuel shares. In addition, our model does not include carbon capture and utilization (CCU) technologies. Specifically, the use of (carbon-neutral) synthetic fuels could be a missing but relevant option to mitigate (net) emissions in the chemical industry, shipping or aviation. However, the cost of deep electrification or CCU could potentially be high and are an active field of research (Fasihi et al., 2016; Hepburn et al., 2019; Madeddu et al., under review). While we underestimate the maximum potential of demand-side mitigation, it is not clear whether we underestimate its cost-optimal deployment in our scenario relative to CDR.

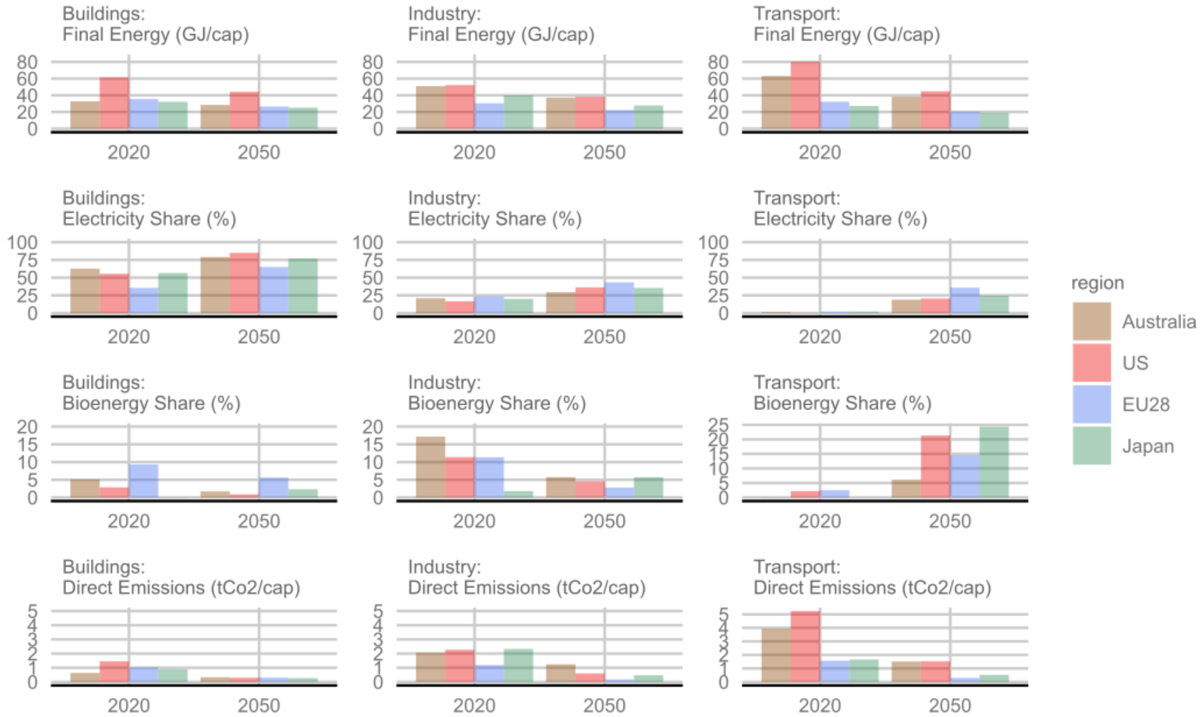


Figure 4: Indicators of demand-side decarbonization across energy end-use sectors in the Net-zero scenario in 2020 and 2050: Final energy consumption per-capita, electricity share of final energy, bioenergy share of final energy and direct demand-side emissions (emissions occurring on site of the energy use excl. emissions from upstream energy production).

Carbon Dioxide Removal Options

CDR by land-use change and BECCS is essential for all regions to reach carbon neutrality by 2050. Reducing gross emissions beyond 90% relative to 2020 levels in each of the four regions is infeasible in our model as residual emissions in the industry and transport sector cannot be avoided.

With full CDR options, Australia offsets an amount of 40% of its 2020 emissions by CDR in 2050, while Japan offsets only 15% (Fig. 5). The carbon price in 2050 (white dots) reflects the marginal cost of abating the last ton of net emissions. Australia requires relatively low carbon prices as it benefits from a large land carbon sequestration potential. Afforestation is generally a low-cost CDR option relative to BECCS and DACCS (Fuss et al., 2018) but is restricted mostly to tropical regions as in mid and high-latitude albedo effects tend to neutralize or even outweigh the cooling effect from sequestered carbon (Bala et al., 2007; Kreidenweis et al., 2016). Japan, in contrast, faces high carbon prices due to limited land-based CDR options and high bioenergy prices.

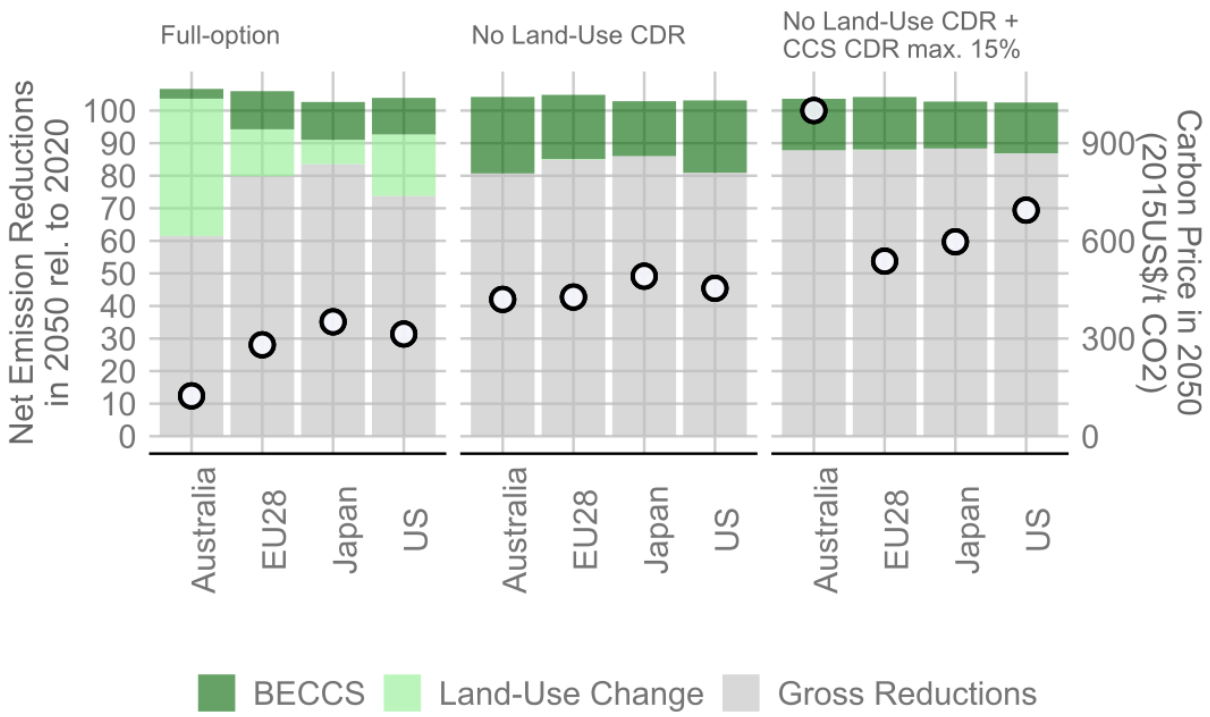


Figure 5: Gross abatement and CDR in 2050 (relative to 2020 net emissions) across net-zero scenarios with different CDR contributions (colored bars, left axis) and corresponding carbon prices in 2050 (white dots, right axis). Full-option is the standard net-zero scenario with all CDR options shown in the previous Figures, "No Land-Use CDR" excludes negative emissions from land-use change but allows for CO2 capture and storage technologies. The "No Land-Use CDR + CCS CDR max. 15%" scenario, moreover, limits CO2 storage to 15% such that at least 85% gross emission reductions relative to 2020 have to be reached.

When constraining the availability of CDR options, we find a shift in the carbon price pattern across the four regions (Fig. 5). If land-use change CDR is not available, carbon prices increase and converge to similar levels across regions since they use BECCS as a more expensive CDR option. However, if in addition CO2 storage is restricted such that gross emission reductions must reach 85% (relative to 2020), Australian and US carbon prices soar, while carbon prices in the EU and Japan hardly increase. Note that here, the carbon price reflects the marginal cost of gross abatement and is not identical to the marginal cost of net abatement as the potential for CDR is limited and fully deployed. The elevated carbon prices of deep gross reductions in Australia and the US result from high energy demand in the industry and transport sector driven by increasing populations and high per-capita energy use (Suppl. Figs. 13 to 15). A similar shift of other cost metrics like GDP loss and energy system cost can be observed across the CDR sensitivity scenarios (see Suppl. S8). The availability of CDR moreover significantly affects emission trajectories after 2050 (see Suppl. S15).

The Net-zero scenario assumes full deployment of regional land carbon potentials based on literature values (Suppl. S2). However, there is considerable uncertainty regarding land-use change (LUC) CDR potentials as estimates depend on assumptions on land availability and management practices (Bryan et al., 2014; Fuss et al., 2018). Moreover, differing accounting methods exist for LUC emissions which has raised the question of whether they should be reported separately or even excluded from national targets (Fyson & Jeffery, 2019). In addition to sustainability concerns of bioenergy expansion, BECCS faces challenges of technological scale-up as well as public acceptance (Nemet et al., 2018). Furthermore, both geological and land carbon storage are not necessarily permanent and require management of leakage and disturbances (Fuss et al., 2018; Galik et al., 2016). DACCS is still too expensive to contribute to carbon neutrality by 2050 in our scenarios. It requires cheap electricity input and is highly land intensive. In case of a significant DACCS cost reduction Australia and the US, in particular, could benefit from its adoption, given their high VRE potential and low population density that facilitates public acceptance.

Conclusions and Outlook

Given their economic capability and historic emissions, there is a normative case for industrialized economies to take leadership roles in global climate change mitigation. Using the modeling tool REMIND, we present corresponding scenarios for representative industrialized regions (EU, US, Japan, and Australia) that achieve domestic net-zero carbon emissions by 2050.

Embarking from different emission profiles and trends, we find that all of the regions have technological options and mitigation strategies to reach carbon neutrality by 2050. Common strategies are a complete power sector decarbonization in 2040, a partial decarbonization of energy demand emissions and a rapid scale-up of CDR technologies. Zooming in, we find a number of region-specific challenges and strengths: While Japan encounters difficulties in the power sector transition due to limited potential for onshore wind and solar power, Australia and the US face challenges to curb industry and transport emissions given increasing populations and high per-capita energy use. The latter regions benefit from large VRE potentials that allow for low-cost renewable electricity generation beyond domestic demand. The role of CDR is particularly important for Australia as the pressure of a fast phase-out of fossil fuels in the growing transport and industry sectors decreases. A large-scale CDR deployment there could significantly alter the required pace, depth and cost of the transition. However, postponing the transition by anticipating future CDR creates serious risks of a carbon lock-in since the scale of available CDR is uncertain. This uncertainty calls for sensible tools of CDR governance where possible remedies such as separating gross emission from negative emission targets and markets have been suggested (McLaren et al., 2019).

Industrialized economies can take a leadership role in the global mitigation effort as the first regions to explore key technologies and policies required for reaching domestic carbon neutrality in 2050. Contributing only about 15% of the cumulative 2011-2100 emissions, their mitigation effort does not significantly affect the remaining 2°C carbon budget of the rest of the world (Suppl. Fig. 17). However, there are a number of channels through which such leadership incentivizes followership in climate mitigation (Schwerhoff et al., 2018): First, technological development and diffusion pushes down learning curves globally and makes abatement for followers cheaper. Second, followers may learn from leaders about best-practice policies, for example, from experience on carbon pricing. Third, leaders resolve uncertainty about abatement options and cost where the followers can learn from their experience. Considering deep decarbonization, this may include region-specific experience on power systems with high VRE shares or the cost-optimal interplay of direct electrification, low-carbon fuels and CDR in hart-to-abate sectors.

This study does not reflect national societal and political circumstances sufficiently to provide region-specific policy advice on how to implement and operate a regional net-zero transition. Due to its global scope, REMIND2.1.2 cannot resolve sub-regional detail as in national models since this would be numerically very demanding (e.g. no explicit representation of power grids or gas infrastructure). Moreover, the representation of national policies and short-term trends remains focused on the most important aspects. IAMs typically take a techno-economic perspective and an improved representation of behavioral and socio-technical aspects is an active area of research (McCollum et al., 2017; Trutnevyte et al., 2019). The strength of our global IAM approach lies in revealing strategic aspects on a comparative cross-regional level: We carve out a number of common and complementary regional patterns of net-zero pathways, which have implications for the international climate policy discourse.

Our findings suggest that it will be crucial for each of the regions to strategically address their respective challenges and uncertainties: Australia and the US may adopt energy efficiency technologies established in the other industrialized economies and invest into their land and agricultural sectors for exploring the feasibility of CDR options. Japan may push for the scale-up of offshore wind technologies while seeking partners to import low-carbon fuels (biofuels, hydrogen, synthetic fuels). As a union of states, the EU faces the challenge of inter-state coordination of VRE-based power systems and power markets. This challenge is less a technological or economic one, but rather one of political cooperation and social acceptance. To what extent the technical VRE potentials in densely populated regions like Europe or Japan can be effectively realized will remain one of the key questions to determine the success of the low-carbon transformation.

Given these regional characteristics, the role of industrialized economies could be one of common but differentiated leadership. They each may lead on different aspects of the low-carbon transition and, if faced with region-specific obstacles, also at different speeds. This has implications for evaluating the Mid-century Strategies (MCS) submitted to the UNFCCC in the post-Paris global stocktake process. Japan's cautious MCS relative to the European MCS, for example, can be justified by techno-economic hurdles the island state faces. Similarly, as long as there is the prospect of CDR, the MCS of Australia and the US should not stay behind the European one.

Finally, a joint leadership effort mindful of regional characteristics gives rise to cooperation potentials and synergies of two kinds. There are cooperation potentials and synergies of two kinds. First, common challenges can be tackled by mutual learning about technology and policy implementations. Japan and the EU may cooperate in advancing electric rail systems to replace short-distance flights. In contrast, finding the cost-optimal trade-off between transforming long-distance passenger and freight transport and potential CDR compensations is a more pressing issue for Australia and the US. Second, industrialized economies could link their complementary transition challenges and strengths. Given their large VRE resource and economic stability, Australia or the US may export electricity-based fuels or materials like hydrogen-based steel to resource constraint countries such as Japan. While there has been exploratory work (Chapman et al., 2017; Fasihi et al., 2016; Gulagi et al., 2017), the jury on VRE-based trade patterns is still out and would require an integrated assessment of entire supply chains. Although, in theory, a joint carbon market can be beneficial, too, there are serious risks involved in such mechanisms as the focus is shifted away from domestic abatement. For example, if each region bet on buying uncertain negative emissions from Australia in the future, they could have an incentive to postpone the near-term transition.

Building a stable leadership coalition that incentivizes followers to join and that minimizes free-riding is subject to extensive literature on international cooperation in climate policy (e.g. Keohane & Victor, 2016; Schwerhoff et al., 2018). For example, the formation of climate clubs has been suggested with few members who would be enticed to participate by exclusive benefits like facilitated trade and investment regulations or joint research and development (Hovi et al., 2016; Victor, 2018). Such strategies can help to set up a leadership coalition as well as to incentivize potential followers to join in. Embarking from groups of industrialized economies to cooperate on specific joint challenges as outlined above could foster coalition building in international climate policy.

Future research should expand the cross-country analysis to total GHG emission abatement including non-CO2 emissions and deepen the assessment of the Mid-century Strategies. Moreover, it could add detail to regional transformation profiles and further explore potential economic and strategic partnerships beyond the categories and regions we analyzed. While this study takes an integrated assessment perspective up to 2050, identifying common themes and synergies is relevant also for short-term entry points and policy design. Such research would provide insight into newly emerging geopolitical and economic trade patterns in a low-carbon world.

References

Bala, G., Caldeira, K., Wickett, M., Phillips, T. J., Lobell, D. B., Delire, C., & Mirin, A. (2007). Combined climate and carbon-cycle effects of large-scale deforestation. *Proceedings of the National Academy of Sciences*, *104*(16), 6550–6555. https://doi.org/10.1073/pnas.0608998104

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*(sup1), S7–S26. https://doi.org/10.1080/14693062.2016.1173005

Bauer, N., Rose, S. K., Fujimori, S., van Vuuren, D. P., Weyant, J., Wise, M., Cui, Y., Daioglou, V., Gidden, M. J., Kato, E., Kitous, A., Leblanc, F., Sands, R., Sano, F., Strefler, J., Tsutsui, J., Bibas, R., Fricko, O., Hasegawa, T., … Muratori, M. (2018). Global energy sector emission reductions and bioenergy use: Overview of the bioenergy demand phase of the EMF-33 model comparison. *Climatic Change*. https://doi.org/10.1007/s10584-018-2226-y

Brown, T. W., Bischof-Niemz, T., Blok, K., Breyer, C., Lund, H., & Mathiesen, B. V. (2018). Response to 'Burden of proof: A comprehensive review of the feasibility of 100% renewable-electricity systems.' *Renewable and Sustainable Energy Reviews*, *92*, 834–847. https://doi.org/10.1016/j.rser.2018.04.113

Bryan, B. A., Nolan, M., Harwood, T. D., Connor, J. D., Navarro-Garcia, J., King, D., Summers, D. M., Newth, D., Cai, Y., Grigg, N., Harman, I., Crossman, N. D., Grundy, M. J., Finnigan, J. J., Ferrier, S., Williams, K. J., Wilson, K. A., Law, E. A., & Hatfield-Dodds, S. (2014). Supply of carbon sequestration and biodiversity services from Australia's agricultural land under global change. *Global Environmental Change*, *28*, 166–181. https://doi.org/10.1016/j.gloenvcha.2014.06.013

Buehler, R. (2011). Determinants of transport mode choice: A comparison of Germany and the USA. *Journal of Transport Geography*, *19*(4), 644–657. https://doi.org/10.1016/j.jtrangeo.2010.07.005

Chapman, A. J., Fraser, T., & Itaoka, K. (2017). Hydrogen import pathway comparison framework incorporating cost and social preference: Case studies from Australia to Japan. *International Journal of Energy Research*, *41*(14), 2374–2391. https://doi.org/10.1002/er.3807

Clack, C. T. M., Qvist, S. A., Apt, J., Bazilian, M., Brandt, A. R., Caldeira, K., Davis, S. J., Diakov, V., Handschy, M. A., Hines, P. D. H., Jaramillo, P., Kammen, D. M., Long, J. C. S., Morgan, M. G., Reed, A., Sivaram, V., Sweeney, J., Tynan, G. R., Victor, D. G., … Whitacre, J. F. (2017). Evaluation of a proposal for reliable low-cost grid power with 100% wind, water, and solar. *Proceedings of the National Academy of Sciences*, 201610381. https://doi.org/10.1073/pnas.1610381114

Climate Action Tracker. (2019). *Governments still showing little sign of acting on climate crisis*. https://climateactiontracker.org/publications/governments-still-not-acting-on-climate-crisis/

ClimateWorks Australia, ANU, CSIRO, & CoPS. (2014). *Pathways to deep decarbonisation in 2050: How Australia can prosper in a low carbon world : technical report*. Technical Report, ClimateWorks Australia. http://www.climateworksaustralia.org/sites/default/files/documents/publications/climateworks_australia_2050_ddpp_technical_report_20140923_final_0.pdf

den Elzen, M., Kuramochi, T., Höhne, N., Cantzler, J., Esmeijer, K., Fekete, H., Fransen, T., Keramidas, K., Roelfsema, M., Sha, F., van Soest, H., & Vandyck, T. (2019). Are the G20 economies making enough progress to meet their NDC targets? *Energy Policy*, *126*, 238–250. https://doi.org/10.1016/j.enpol.2018.11.027

EU. (2020). *Submission by Croatia and the European Commission on behalf of the European Union and its Member States*. https://unfccc.int/sites/default/files/resource/HR-03-06-2020%20EU%20Submission%20on%20Long%20term%20strategy.pdf

EU Commission. (2018). *In-depth anlysis in support of the Comission Communication COM(2018) 773A. Clean Planet for allA European long-term strategic vision for a prosperous, modern, competitive and climate neutral economy*.

https://ec.europa.eu/clima/sites/clima/files/docs/pages/com_2018_733_analysis_in_support_en_0.pdf

Fasihi, M., Bogdanov, D., & Breyer, C. (2016). Techno-Economic Assessment of Power-to-Liquids (PtL) Fuels Production and Global Trading Based on Hybrid PV-Wind Power Plants. *Energy Procedia*, *99*, 243–268. https://doi.org/10.1016/j.egypro.2016.10.115

Fragkos, P., Tasios, N., Paroussos, L., Capros, P., & Tsani, S. (2017). Energy system impacts and policy implications of the European Intended Nationally Determined Contribution and low-carbon pathway to 2050. *Energy Policy*, *100*, 216–226. https://doi.org/10.1016/j.enpol.2016.10.023

Fuss, S., Lamb, W. F., Callaghan, M. W., Hilaire, J., Creutzig, F., Amann, T., Tim Beringer, Garcia, W. de O., Hartmann, J., Khanna, T., Luderer, G., Nemet, G. F., Joeri Rogelj, Smith, P., Vicente, J. L. V., Wilcox, J., Dominguez, M. del M. Z., & Minx, J. C. (2018). Negative emissions—Part 2: Costs, potentials and side effects. *Environmental Research Letters*, *13*(6), 063002. https://doi.org/10.1088/1748-9326/aabf9f

Fyson, C. L., & Jeffery, M. L. (2019). Ambiguity in the Land Use Component of Mitigation Contributions Toward the Paris Agreement Goals. *Earth's Future*, *7*(8), 873–891. https://doi.org/10.1029/2019EF001190

Galik, C. S., Murray, B. C., Mitchell, S., & Cottle, P. (2016). Alternative approaches for addressing non-permanence in carbon projects: An application to afforestation and reforestation under the Clean Development Mechanism. *Mitigation and Adaptation Strategies for Global Change*, *21*(1), 101–118. https://doi.org/10.1007/s11027-014-9573-4

Grassi, G., House, J., Kurz, W. A., Cescatti, A., Houghton, R. A., Peters, G. P., Sanz, M. J., Viñas, R. A., Alkama, R., Arneth, A., Bondeau, A., Dentener, F., Fader, M., Federici, S., Friedlingstein, P., Jain, A. K., Kato, E., Koven, C. D., Lee, D., … Zaehle, S. (2018). Reconciling global-model estimates and country reporting of anthropogenic forest CO2 sinks. *Nature Climate Change*, *8*(10), 914–920. https://doi.org/10.1038/s41558-018-0283-x

Gulagi, A., Bogdanov, D., Fasihi, M., & Breyer, C. (2017). Can Australia Power the Energy-Hungry Asia with Renewable Energy? *Sustainability*, *9*(2), 233. https://doi.org/10.3390/su9020233

Gütschow, J., Jeffery, L., Gieseke, R., & Gebel, R. (2017). *The PRIMAP-hist national historical emissions time series (1850-2014). V. 1.1*. https://doi.org/10.5880/PIK.2017.001

Gütschow, J., Jeffery, L., Gieseke, R., & Günther, A. (2019). *The PRIMAP-hist national historical emissions time series (1850-2017). V. 2.1*. https://doi.org/10.5880/PIK.2019.018

Gütschow, J., Jeffery, M. L., Gieseke, R., Gebel, R., Stevens, D., Krapp, M., & Rocha, M. (2016). The PRIMAP-hist national historical emissions time series. *Earth System Science Data*, *8*, 33. https://doi.org/doi:10.5194/essd-8-571-2016

Hansen, K., Breyer, C., & Lund, H. (2019). Status and perspectives on 100% renewable energy systems. *Energy*, *175*, 471–480. https://doi.org/10.1016/j.energy.2019.03.092

Harper, M., Anderson, B., James, P., & Bahaj, A. (2019). Assessing socially acceptable locations for onshore wind energy using a GIS-MCDA approach. *International Journal of Low-Carbon Technologies*, *14*(2), 160–169. https://doi.org/10.1093/ijlct/ctz006

Heard, B. P., Brook, B. W., Wigley, T. M. L., & Bradshaw, C. J. A. (2017). Burden of proof: A comprehensive review of the feasibility of 100% renewable-electricity systems. *Renewable and Sustainable Energy Reviews*, *76*, 1122–1133. https://doi.org/10.1016/j.rser.2017.03.114

Hepburn, C., Adlen, E., Beddington, J., Carter, E. A., Fuss, S., Mac Dowell, N., Minx, J. C., Smith, P., & Williams, C. K. (2019). The technological and economic prospects for CO2 utilization and removal. *Nature*, *575*(7781), 87–97. https://doi.org/10.1038/s41586-019-1681-6

Honma, S., & Hu, J.-L. (2014). Industry-level total-factor energy efficiency in developed countries: A Japan-centered analysis. *Applied Energy*, *119*, 67–78. https://doi.org/10.1016/j.apenergy.2013.12.049

Hope, M. (2020). Australia burning. *The Lancet Planetary Health*, *4*(1). https://doi.org/10.1016/S2542-5196(20)30006-1

Hovi, J., Sprinz, D. F., Sælen, H., & Underdal, A. (2016). Climate change mitigation: A role for climate clubs? *Palgrave Communications*, *2*(1), 16020. https://doi.org/10.1057/palcomms.2016.20

Huppmann, D., Kriegler, E., Krey, V., Riahi, K., Rogelj, J., Rose, S. K., Weyant, J., Bauer, N., Bertram, C., Bosetti, V., Calvin, K., Doelman, J., Drouet, L., Emmerling, J., Frank, S., Fujimori, S., Gernaat, D., Grubler, A., Guivarch, C., … Zhang, R. (2018). *IAMC 1.5°C Scenario Explorer and Data hosted by IIASA*. Integrated Assessment Modeling Consortium & International Institute for Applied Systems Analysis. https://doi.org/10.22022/SR15/08-2018.15429

IEA. (2017). *Extended world energy balances* [(Database)]. IEA World Energy Statistics and Balances. http://dx.doi.org/10.1787/data-00513-en

IPCC. (2018). *Global warming of 1.5C. An IPCC Special Report on the impacts of global warming of 1.5° above pre-industrial levels and related global greenhouse gas emissions pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty*. World Meteorological Organization.

IRENA. (2019). *Renewable power generation costs in 2018*. International Renewable Energy Agency. https://www.irena.org/publications/2019/May/Renewable-power-generation-costs-in-2018

Jacobson, M. Z., Delucchi, M. A., Bazouin, G., Bauer, Z. A. F., Heavey, C. C., Fisher, E., Morris, S. B., Piekutowski, D. J. Y., Vencill, T. A., & Yeskoo, T. W. (2015). 100% clean and renewable wind, water, and sunlight (WWS) all-sector energy roadmaps for the 50 United States. *Energy & Environmental Science*, *8*(7), 2093–2117. https://doi.org/10.1039/C5EE01283J

James, S. L., Gubbins, P., Murray, C. J., & Gakidou, E. (2012). Developing a comprehensive time series of GDP per capita for 210 countries from 1950 to 2015. *Population Health Metrics*, *10*(1), 12. https://doi.org/10.1186/1478-7954-10-12

JISF. (2019). *Long-term vision for climate change mitigation. A challenge towards zero-carbon steel*. The Japan Iron and Steel Federation. https://www.jisf.or.jp/en/activity/climate/documents/JISFLong-termvisionforclimatechangemitigation_text.pdf

Kato, E., & Kurosawa, A. (2019). Evaluation of Japanese energy system toward 2050 with TIMES-Japan – deep decarbonization pathways. *Energy Procedia*, *158*, 4141–4146. https://doi.org/10.1016/j.egypro.2019.01.818

Kędzierski, M. (2019). *German wind power sector in crisis Energiewende under further threat*. *309*, 8. http://aei.pitt.edu/102321/1/commentary_309.pdf

Keohane, R. O., & Victor, D. G. (2016). Cooperation and discord in global climate policy. *Nature Climate Change*, *6*(6), 570–575. https://doi.org/10.1038/nclimate2937

Kreidenweis, U., Humpenöder, F., Stevanović, M., Bodirsky, B. L., Kriegler, E., Lotze-Campen, H., & Popp, A. (2016). Afforestation to mitigate climate change: Impacts on food prices under consideration of albedo effects. *Environmental Research Letters*, *11*(8), 085001. https://doi.org/10.1088/1748-9326/11/8/085001

Krey, V., Guo, F., Kolp, P., Zhou, W., Schaeffer, R., Awasthy, A., Bertram, C., de Boer, H.-S., Fragkos, P., Fujimori, S., He, C., Iyer, G., Keramidas, K., Köberle, A. C., Oshiro, K., Reis, L. A., Shoai-Tehrani, B., Vishwanathan, S., Capros, P., … van Vuuren, D. P. (2019). Looking under the hood: A comparison of techno-economic assumptions across national and global integrated assessment models. *Energy*, *172*, 1254–1267. https://doi.org/10.1016/j.energy.2018.12.131

Kriegler, E., Bauer, N., Popp, A., Humpenöder, F., Leimbach, M., Strefler, J., Baumstark, L., Bodirsky, B. L., Hilaire, J., Klein, D., Mouratiadou, I., Weindl, I., Bertram, C., Dietrich, J.-P., Luderer, G., Pehl, M., Pietzcker, R., Piontek, F., Lotze-Campen, H., … Edenhofer, O. (2017). Fossil-fueled development (SSP5): An energy and resource intensive scenario for the 21st century. *Global Environmental Change*, *42*, 297–315. https://doi.org/10.1016/j.gloenvcha.2016.05.015

Lechtenböhmer, S., Nilsson, L. J., Åhman, M., & Schneider, C. (2016). Decarbonising the energy intensive basic materials industry through electrification – Implications for future EU electricity demand. *Energy*, *115*, 1623–1631. https://doi.org/10.1016/j.energy.2016.07.110

Lempert, R., Preston, B., Edmonds, J., Clarke, L., Wild, T., & Binsted, M. (2019). *Pathways to 2050: Alternative Scenarios for the Decarbonizing the U.S. Economy*. https://www.c2es.org/document/pathways-to-2050-scenarios-for-decarbonizing-the-u-s-economy/

Levesque, A., Pietzcker, R. C., Baumstark, L., De Stercke, S., Grübler, A., & Luderer, G. (2018). How much energy will buildings consume in 2100? A global perspective within a scenario framework. *Energy*, *148*, 514–527. https://doi.org/10.1016/j.energy.2018.01.139

Lipscy, P. Y., & Schipper, L. (2013). Energy efficiency in the Japanese transport sector. *Energy Policy*, *56*, 248–258. https://doi.org/10.1016/j.enpol.2012.12.045

Lotze-Campen, H., Müller, C., Bondeau, A., Rost, S., Popp, A., & Lucht, W. (2008). Global food demand, productivity growth, and the scarcity of land and water resources: A spatially explicit mathematical programming approach. *Agricultural Economics*, *39*(3), 325–338. https://doi.org/10.1111/j.1574-0862.2008.00336.x

Luderer, G., Bauer, N., Baumstark, L., Bertram, C., Leimbach, M., Pietzcker, R., Strefler, J., Aboumahboub, T., Auer, C., Bauer, N., Baumstark, L., Bertram, C., Bi, S., Dietrich, J., Dirnaichner, A., Giannousakis, A., Haller, M., Hilaire, J., Klein, D., … Ueckerdt, F. (2020). *REMIND - REgional Model of INvestments and Development* (Version 2.1.2) [Computer software]. Zenodo. https://doi.org/10.5281/zenodo.3899869

Luderer, G., Leimbach, M., Bauer, N., Kriegler, E., Baumstark, L., Bertram, C., Giannousakis, A., Hilaire, J., Klein, D., Levesque, A., Mouratiadou, I., Pehl, M., Pietzcker, R., Piontek, F., Roming, N., Schultes, A., Schwanitz, V. J., & Strefler, J. (2015). *Description of the REMIND Model (Version 1.6)* (SSRN Scholarly Paper ID 2697070). Social Science Research Network. https://papers.ssrn.com/abstract=2697070

Luderer, G., Vrontisi, Z., Bertram, C., Edelenbosch, O. Y., Pietzcker, R. C., Rogelj, J., De Boer, H. S., Drouet, L., Emmerling, J., Fricko, O., Fujimori, S., Havlík, P., Iyer, G., Keramidas, K., Kitous, A., Pehl, M., Krey, V., Riahi, K., Saveyn, B., … Kriegler, E. (2018). Residual fossil CO2 emissions in 1.5–2 °C pathways. *Nature Climate Change*, *8*(7), 626–633. https://doi.org/10.1038/s41558-018-0198-6

Madeddu, S., Ueckerdt, F., Pehl, M., Peterseim, J., Lord, M., Kumar, K. A., Krüger, C., & Luderer, G. (under review). *The CO2 reduction potential for industry via direct electrification of heat supply (power-to-heat)*.

Marcucci, A., & Fragkos, P. (2015). Drivers of regional decarbonization through 2100: A multi-model decomposition analysis. *Energy Economics*, *51*, 111–124. https://doi.org/10.1016/j.eneco.2015.06.009

Mazengarb, M. (2020, February 25). Australia already has a net zero emissions target, only the Morrison government denies it. *Reneweconomy*. https://reneweconomy.com.au/australia-already-has-a-net-zero-emissions-target-only-the-morrison-government-denies-it-36365/

McCollum, D. L., Wilson, C., Pettifor, H., Ramea, K., Krey, V., Riahi, K., Bertram, C., Lin, Z., Edelenbosch, O. Y., & Fujisawa, S. (2017). Improving the behavioral realism of global integrated assessment models: An application to consumers' vehicle choices. *Transportation Research Part D: Transport and Environment*, *55*, 322–342. https://doi.org/10.1016/j.trd.2016.04.003

McLaren, D. P., Tyfield, D. P., Willis, R., Szerszynski, B., & Markusson, N. O. (2019). Beyond "Net-Zero": A Case for Separate Targets for Emissions Reduction and Negative Emissions. *Frontiers in Climate*, *1*, 4. https://doi.org/10.3389/fclim.2019.00004

Mizuno, E. (2014). Overview of wind energy policy and development in Japan. *Renewable and Sustainable Energy Reviews*, *40*, 999–1018. https://doi.org/10.1016/j.rser.2014.07.184

MOE Japan. (2020). *2050 Zero Carbon Cities in Japan*. Ministry of the Environment, Government of Japan. http://www.env.go.jp/en/earth/cc/2050_zero_carbon_cities_in_japan.html

Nemet, G. F., Callaghan, M. W., Creutzig, F., Fuss, S., Hartmann, J., Hilaire, J., Lamb, W. F., Minx, J. C., Rogers, S., & Smith, P. (2018). Negative emissions—Part 3: Innovation and upscaling. *Environmental Research Letters*, *13*(6), 063003. https://doi.org/10.1088/1748-9326/aabff4

Ocasio-Cortez, A. (2019). *H.Res.109—Recognizing the duty of the Federal Government to create a Green New Deal.* U.S. House of Representatives. https://www.congress.gov/bill/116th-congress/house-resolution/109/text

Oshiro, K., Gi, K., Fujimori, S., van Soest, H. L., Bertram, C., Després, J., Masui, T., Rochedo, P., Roelfsema, M., & Vrontisi, Z. (2019). Mid-century emission pathways in Japan associated with the global 2 °C goal: National and global models' assessments based on carbon budgets. *Climatic Change*. https://doi.org/10.1007/s10584-019-02490-x

Oshiro, K., Masui, T., & Kainuma, M. (2018). Transformation of Japan’s energy system to attain net-zero emission by 2050. *Carbon Management*, *9*(5), 493–501. https://doi.org/10.1080/17583004.2017.1396842

Pietzcker, R. C., Ueckerdt, F., Carrara, S., de Boer, H. S., Després, J., Fujimori, S., Johnson, N., Kitous, A., Scholz, Y., Sullivan, P., & Luderer, G. (2017). System integration of wind and solar power in integrated assessment models: A cross-model evaluation of new approaches. *Energy Economics*, *64*, 583–599. https://doi.org/10.1016/j.eneco.2016.11.018

Popp, A., Rose, S. K., Calvin, K., Vuuren, D. P. V., Dietrich, J. P., Wise, M., Stehfest, E., Humpenöder, F., Kyle, P., Vliet, J. V., Bauer, N., Lotze-Campen, H., Klein, D., & Kriegler, E. (2014). Land-use transition for bioenergy and climate stabilization: Model comparison of drivers, impacts and interactions with other land use based mitigation options. *Climatic Change*, *123*(3–4), 495–509. https://doi.org/10.1007/s10584-013-0926-x

Riahi, K., van Vuuren, D. P., Kriegler, E., Edmonds, J., O’Neill, B. C., Fujimori, S., Bauer, N., Calvin, K., Dellink, R., Fricko, O., Lutz, W., Popp, A., Cuaresma, J. C., Kc, S., Leimbach, M., Jiang, L., Kram, T., Rao, S., Emmerling, J., … Tavoni, M. (2017). The Shared Socioeconomic Pathways and their energy, land use, and greenhouse gas emissions implications: An overview. *Global Environmental Change*, *42*, 153–168. https://doi.org/10.1016/j.gloenvcha.2016.05.009

Ringkjøb, H.-K., Haugan, P. M., & Solbrekke, I. M. (2018). A review of modelling tools for energy and electricity systems with large shares of variable renewables. *Renewable and Sustainable Energy Reviews*, *96*, 440–459. https://doi.org/10.1016/j.rser.2018.08.002

Rogelj, J., den Elzen, M., Höhne, N., Fransen, T., Fekete, H., Winkler, H., Schaeffer, R., Sha, F., Riahi, K., & Meinshausen, M. (2016). Paris Agreement climate proposals need a boost to keep warming well below 2 °C. *Nature*, *534*(7609), 631–639. https://doi.org/10.1038/nature18307

Rottoli, M., Dirnacher, A., Kyle, P., Baumstark, L., Pietzcker, R., & Luderer, G. (under review). *Coupling a detailed transport model to the Integrated Assessment Model REMIND*.

Schandl, H., & West, J. (2012). Material Flows and Material Productivity in China, Australia, and Japan. *Journal of Industrial Ecology*, *16*(3), 352–364. https://doi.org/10.1111/j.1530-9290.2011.00420.x

Scholz, Y., Gils, H. C., & Pietzcker, R. C. (2017). Application of a high-detail energy system model to derive power sector characteristics at high wind and solar shares. *Energy Economics*, *64*(Supplement C), 568–582. https://doi.org/10.1016/j.eneco.2016.06.021

Schwerhoff, G., Kornek, U., Lessmann, K., & Pahle, M. (2018). Leadership in climate change mitigation: Consequences and incentives. *Journal of Economic Surveys*, *32*(2), 491–517. https://doi.org/10.1111/joes.12203

Steinberg, D., Bielen, D., Eichman, J., Eurek, K., Logan, J., Mai, T., McMillan, C., Parker, A., Vimmerstedt, L., & Wilson, E. (2017). Electrification & Decarbonization: Exploring U.S. Energy Use and Greenhouse Gas Emissions in Scenarios with Widespread Electrification and Power Sector Decarbonization. *Renewable Energy*, 53.

Steward, D. (2009). Japan: The power of efficiency. In A. Gal Luft Korin (Ed.), *Energy Security Challenges for the 21st Century: A Reference Handbook* (pp. 176–190). Praeger Security International.

Strefler, J., Bauer, N., Kriegler, E., Popp, A., Giannousakis, A., & Edenhofer, O. (2018). Between Scylla and Charybdis: Delayed mitigation narrows the passage between large-scale CDR and high costs. *Environmental Research Letters*, *13*(4), 044015. https://doi.org/10.1088/1748-9326/aab2ba

Sugiyama, M., Fujimori, S., Wada, K., Endo, S., Fujii, Y., Komiyama, R., Kato, E., Kurosawa, A., Matsuo, Y., Oshiro, K., Sano, F., & Shiraki, H. (2019). Japan's long-term climate mitigation policy: Multi-model assessment and sectoral challenges. *Energy*, *167*, 1120–1131. https://doi.org/10.1016/j.energy.2018.10.091

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*, *advance online publication*. https://doi.org/10.1038/nclimate2475

Tokyo Metropolitan Government. (2019). *Zero Emission Tokyo. A decarbonization strategy to realize a Tokyo that serves as a pioneer for our brilliant future*. https://www.kankyo.metro.tokyo.lg.jp/en/about_us/zero_emission_tokyo/strategy.files/Full-ver.ZE-strategy0311.pdf

Trutnevyte, E., Hirt, L. F., Bauer, N., Cherp, A., Hawkes, A., Edelenbosch, O. Y., Pedde, S., & van Vuuren, D. P. (2019). Societal Transformations in Models for Energy and Climate Policy: The Ambitious Next Step. *One Earth*, *1*(4), 423–433. https://doi.org/10.1016/j.oneear.2019.12.002

Ueckerdt, F., Dargaville, R., Gils, H.-C., McConnell, D., Meinshausen, M., Scholz, Y., Schreyer, F., & Wang, C. (2019). *Australia's power advantage. Energy transition and hydrogen export scenarios*. Energy Transition Hub. https://www.energy-transition-hub.org/files/resource/attachment/australia_power_advantage_0.pdf

Ueckerdt, F., Hirth, L., Luderer, G., & Edenhofer, O. (2013). System LCOE: What are the costs of variable renewables? *Energy*, *63*(Supplement C), 61–75. https://doi.org/10.1016/j.energy.2013.10.072

Ueckerdt, F., Pietzcker, R., Scholz, Y., Stetter, D., Giannousakis, A., & Luderer, G. (2017). Decarbonizing global power supply under region-specific consideration of challenges and options of integrating variable renewables in the REMIND model. *Energy Economics*, *64*, 665–684. https://doi.org/10.1016/j.eneco.2016.05.012

UNFCCC. (2015). *Adoption of the Paris Agreement* (FCCC/CP/2015/L.9/Rev.1). United Nations Framework Convention on Climate Change. http://unfccc.int/resource/docs/2015/cop21/eng/l09r01.pdf

Van Sluisveld, M. a. E., Gernaat, D. E. H. J., Ashina, S., Calvin, K. V., Garg, A., Isaac, M., Lucas, P. L., Mouratiadou, I., Otto, S. a. C., Rao, S., Shukla, P. R., Van Vliet, J., & Van Vuuren, D. P. (2013).

A multi-model analysis of post-2020 mitigation efforts of five major economies. *Climate Change Economics*, *04*(04), 1340012. https://doi.org/10.1142/S2010007813400125

van Soest, H. L., Aleluia Reis, L., Drouet, L., van Vuuren, D. P., den Elzen, M. G. J., Tavoni, M., Akimoto, K., Calvin, K. V., Fragkos, P., Kitous, A., Luderer, G., & Riahi, K. (2017). Low-emission pathways in 11 major economies: Comparison of cost-optimal pathways and Paris climate proposals. *Climatic Change*, *142*(3–4), 491–504. https://doi.org/10.1007/s10584-017-1964-6

Victor, D. G. (2018). The new geometry of climate governance. *Chinese Journal of Population Resources and Environment*, *16*(3), 181–185. https://doi.org/10.1080/10042857.2018.1487185

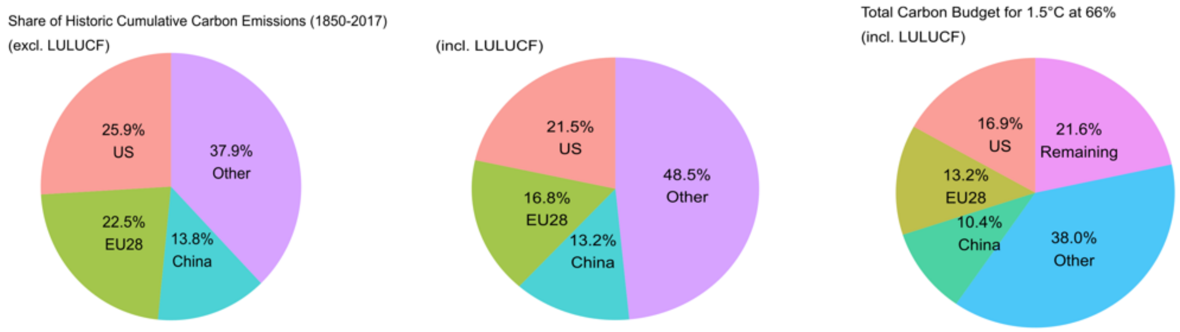
Vivoda, V. (2012). Japan’s energy security predicament post-Fukushima. *Energy Policy*, *46*, 135–143. https://doi.org/10.1016/j.enpol.2012.03.044

Vrontisi, Z., Fragkiadakis, K., Kannavou, M., & Capros, P. (2019). Energy system transition and macroeconomic impacts of a European decarbonization action towards a below 2 °C climate stabilization. *Climatic Change*. https://doi.org/10.1007/s10584-019-02440-7

Warr, B., Ayres, R., Eisenmenger, N., Krausmann, F., & Schandl, H. (2010). Energy use and economic development: A comparative analysis of useful work supply in Austria, Japan, the United Kingdom and the US during 100 years of economic growth. *Ecological Economics*, *69*(10), 1904–1917.

Supplementary Material

S1. Historic cumulative emission shares



*Suppl. Figure 1: **Left and Center**: Shares of Historic Cumulative Carbon Emissions (1850-2017) across US, EU28 and China including and excluding emissions from land-use change. Historic land-use carbon emissions come with substantial uncertainty due to different data reporting methodologies. In addition, they mostly occur in developing countries, but are induced by supply chains to industrialized countries such that consumption-based and production-based emission attribution has significant impact on the result. Here, we report production-based emissions. **Right:** Total carbon budget for a 66% chance of climate stabilization at 1.5°C (2770 Gt CO_2, see IPCC, 2018): regional shares of historic cumulative emissions and the remaining global budget (post-2016). Historic emissions are from Gütschow et al. (2016, 2017, 2019).*

S2. Model description and regional adjustments

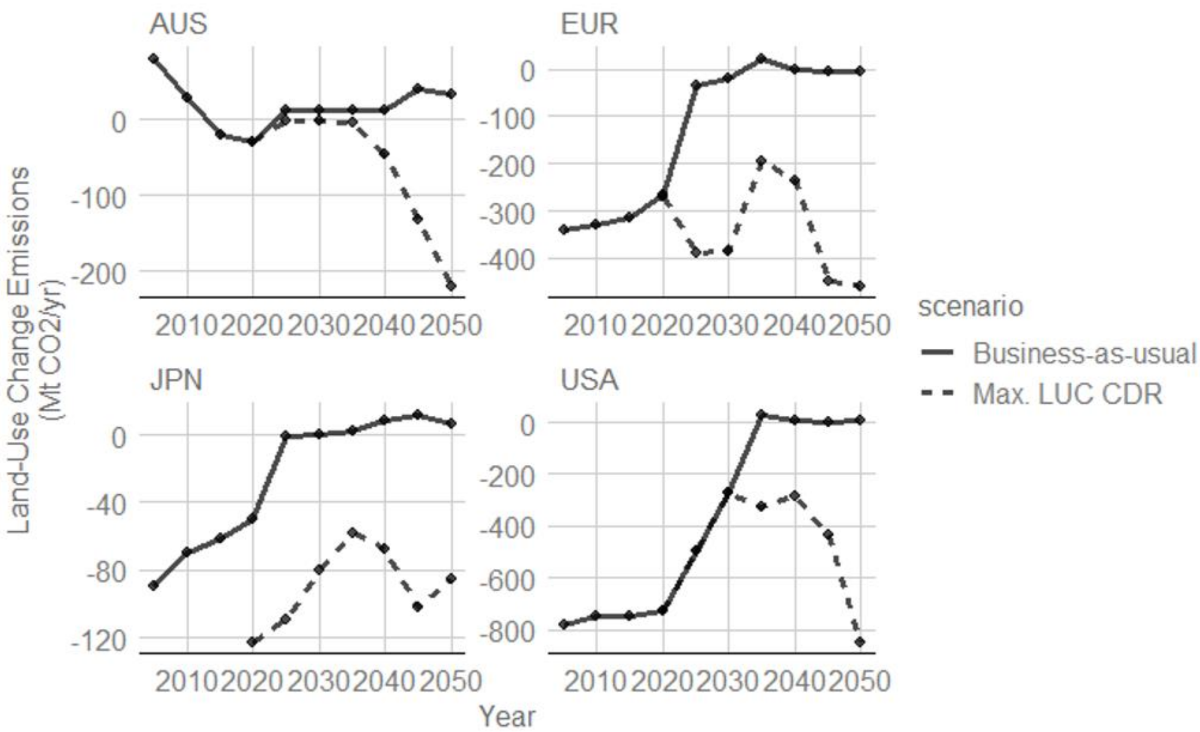
In the following section, we provide details and further literature about the REMIND model. The REMIND 2.1.2 version is accessible open-source (Luderer et al., 2020)A comprehensive model description is given by Luderer et al. (2015), yet for an earlier version of the REMIND model. In the following, we summarize key aspects of the model dynamics and features.

To calibrate the CES production function, we make assumptions about future regional energy demand trajectories based on historic demand patterns and use GDP and population scenarios from the SSP2 “middle of the road” scenario (Riahi et al., 2017). In addition, REMIND uses emulators derived from the detailed land-use and agricultural model MAgPIE (Lotze-Campen et al., 2008; Popp et al., 2014) for representing bioenergy supply costs and land carbon mitigation options. The model can generate negative emissions by bioenergy with carbon capture and storage (BECCS) and direct air capture with CO2 storage (DACCS).

Regarding primary energy carriers, the model represents extraction of fossil energy and uranium and all regions can trade primary energy fuels (coal, gas, oil, biomass, uranium) via a common global pool. Hence, primary energy prices are affected by the domestic extraction cost as well as the world market price. Trade of secondary energy (e.g. hydrogen, electricity) is not included.

The model furthermore contains a representation of relevant (non-carbon) policies. They serve to capture (current) regional differences in prices of final energy carriers and plausible short-term trends of the energy system. First, the model includes taxes and subsidies on final energy carriers (e.g. on electricity for households or industry, for liquid fuels in transport) and extraction of primary energy carriers to represent current prices patterns. In our scenarios, we assume that regional non-carbon taxes are kept in the future, while subsidies are phased-out gradually up to 2050. Second, we make assumptions about the short-term development of the energy system in each region by imposing capacity targets for 2030 in line with the National Determined Contributions (NDCs) of UNFCCC member states reported between 2015-2017. These 2030 technology capacity targets are lower bounds to the model optimization and ensure representation of short-term trends in the energy system according to the current NDC plans.

To ensure consistency with officially reported land-use change (LUC) emissions and align the associated carbon dioxide removal (CDR) potential with literature, we do some region-specific adjustments for the four regions in focus. Generally, for land-use change emissions in REMIND, we apply a marginal abatement cost curve between a MAgPIE baseline scenario (without carbon price) and a maximum CDR scenario. The higher the carbon price, the more LUC emissions will shift from the baseline scenario to the maximum CDR scenario. The curves we used for both regions are shown in Suppl. Fig. 6. However, it is a known problem that there can be significant differences between modeled and officially reported LUC emissions (Grassi et al., 2018). To ensure consistency with reported data, we adjusted the MAgPie output. First, we adjust to the officially reported values until 2015 and extrapolate the trend to 2020 in the four regions (EU, Australia, US, Japan). Second, for the baseline scenario, we chose to decrease LUC emissions from net removals in 2020 to net-zero latest by 2040. This is a conservative assumption given that LUC emissions had been negative across the four regions over at least the past decade. After 2040, the baseline land-use change emissions follow the MAgPIE baseline run and remain at levels close to net-zero. Third, we rescaled the maximum CDR LUC emission trajectory to align with literature-based levels for 2050 presented in Suppl. Table 1.



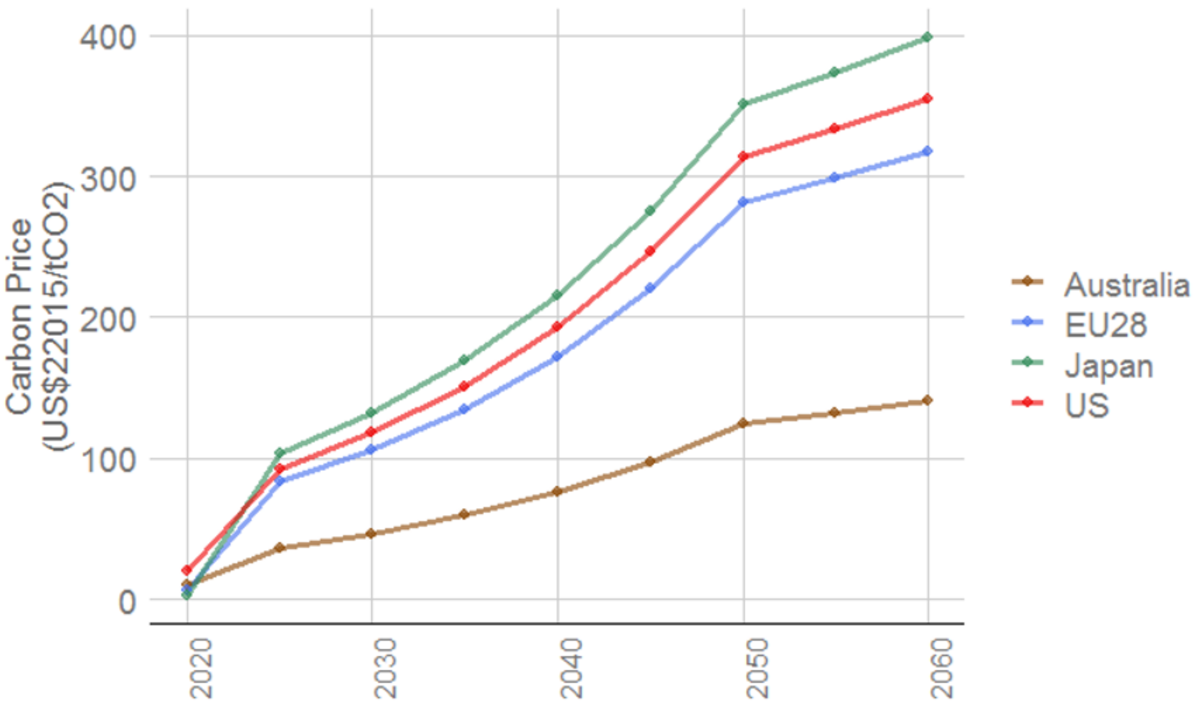
Suppl. Figure 2: Assumptions on baseline land-use change emissions (at zero carbon price) and maximum possible negative emissions by land-use change in MtCO2//yr.

Region	**Maximum Land-Use Change CDR Potential in 2050 (Mt CO2/yr)**	**Source**
Australia	220	Bryan et al. (2014), based on Fig. 6 scenario "M3"
US	850	Johnson et al. (2010), The White House (2016, p. 69)
EU	460	European Commission (2018, p. 185)
Japan	85	Matsumoto et al. (2016), only afforestation and no carbon price applied. We took the optimistic scenario of low wood demand ("baseline").

Suppl. Table 1: Assumptions on maximum CDR potential of land-use change by 2050 used in the scenarios with full CDR options.

S3. Carbon price trajectories

The shape of the carbon price trajectories over time are exogenous to the model, while the level of the carbon price is adjusted iteratively until the 2050 net-zero target is reached. To exemplify the trajectories, Suppl. Figure 5 shows the carbon price of the *Net-zero* scenario. The carbon price in 2020 reflects current policy ambition based on the Nationally Determined Contributions (NDCs) of the regions according to the Paris Agreement. From 2025 onwards, the carbon price trajectory increases exponentially at a rate of 5% per year (corresponding to discount rate of the model in line with the Hotelling rule) to meet the net-zero target in 2050. After 2050, the carbon price increases linearly until 2100. The reasoning behind this post-2050 shift is that in 1.5°C to 2°C scenarios global carbon neutrality is typically reached in the beginning of the second half of the century. If the trajectory remained exponential afterwards, this would result in very high carbon prices and large net negative emissions globally. However, our above scenarios follow the idea of reaching a 2°C stabilization without the need to reduce temperature afterwards. To avoid an extreme net-negative emissions world in our scenarios, we reduce the carbon price increase after 2050.

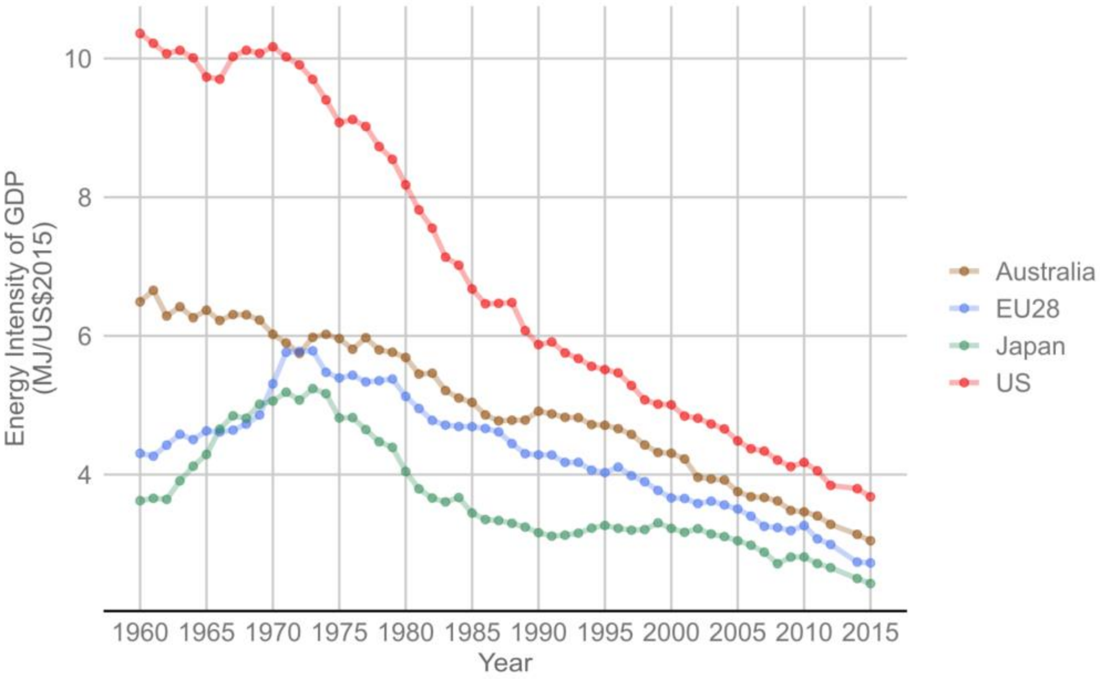


Suppl. Figure 3: Carbon price trajectories of the Net-zero scenario in US$2015/tCO2.

S4. The Current Policies scenario

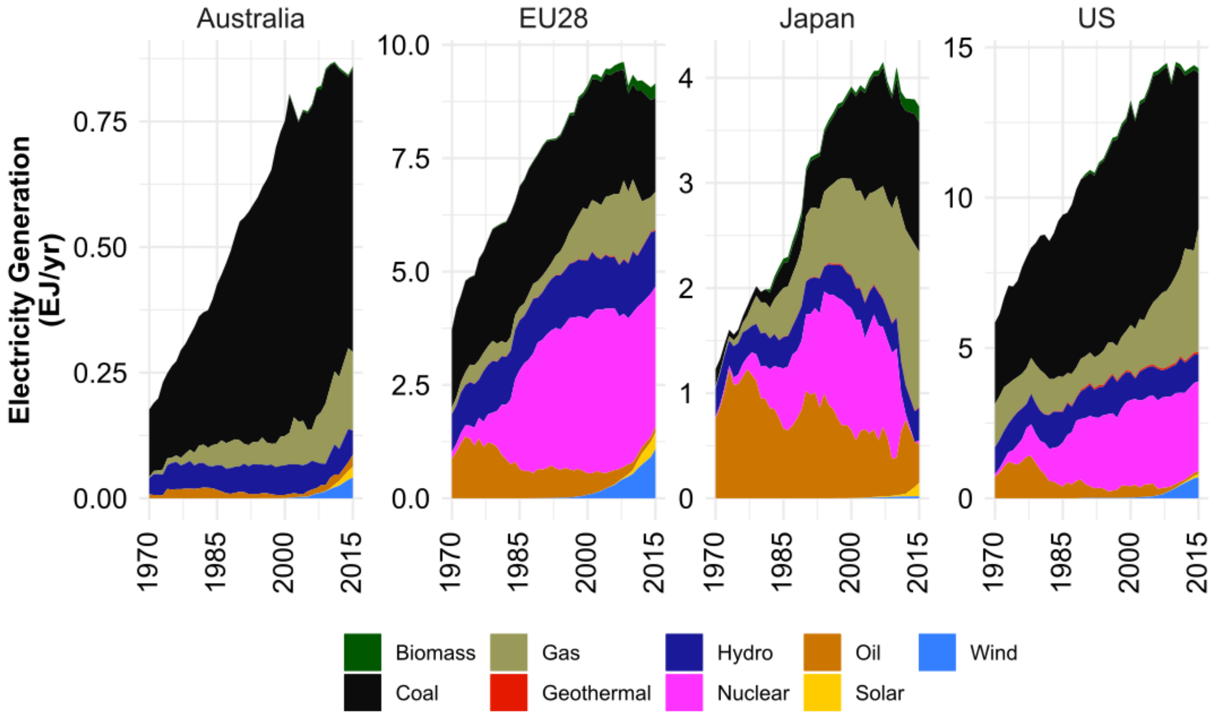
Our *Current Policies* scenario is constructed in the following way: We first run a scenario in line with the National Determined Contributions (NDCs) of the Paris Agreement in terms of emission reductions and technological targets (such as renewable energy targets) for 2030. All our scenarios (also the net-zero scenarios) assume the 2020 carbon price generated by the NDC run as we assume that current policy ambitions reflect efforts to reach the 2030 NDC targets. However, we assume in the *Current Policies* scenario that policies for reaching the 2030 NDC targets will not be strengthened and the carbon price remains at levels similar to 2020, converging across regions to reach 14 \$2015/t CO_2 by 2100.

S5. Historic energy intensity of GDP



Suppl. Figure 4: Final energy intensity of GDP between 1960 and 2015 in MJ/US$2015 for the four regions based on data from IEA (2017) and James et al. (2012).

S6. Historical development of the electricity mix (1970-2015)



Suppl. Figure 5: Historical 1970-2015 electricity mix across the four regions based on data from the IEA (2017).

S7. Integration Cost

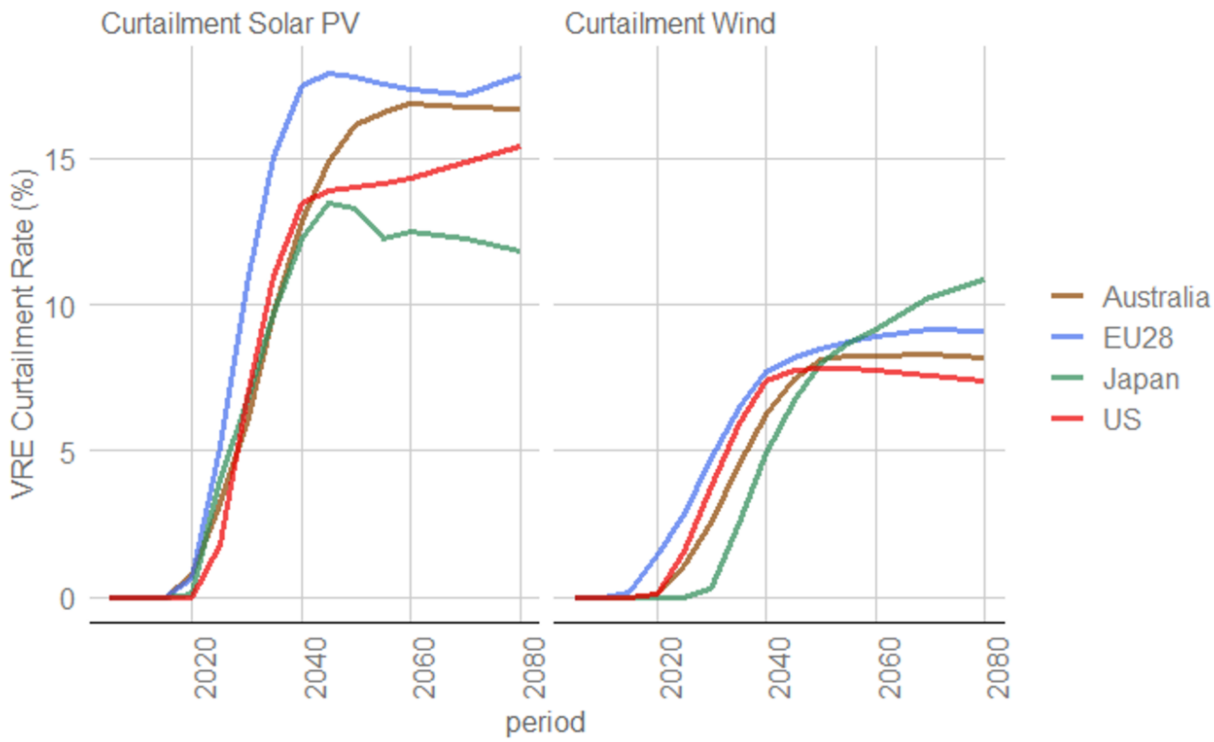
The REMIND model results show power sector transition pathways that reach a full decarbonization between 2040 and 2050 in three of four focus regions (US, EU and Australia , see Figure 3). Electricity demand is supplied from close to 100% renewable energy sources, of which a major share is coming from variable sources of wind and solar PV power (variable or sometimes called *intermittent*, i.e. weather and seasonal dependent). In the following, we answer two related important questions on renewables integration and provide key references. First, how are challenges of integrating high shares of wind and solar PV represented in global IAMs like REMIND? Second, are high share of variable renewable power technically and economically feasible; and if so, what are the technical measures that make such systems manageable?

Substantial work has been conducted in the recent years to improve the representation of challenges and options of wind and solar PV integration in IAMs. In the ADVANCE project, six international IAM teams have developed and implemented new approaches. Pietzcker et al. (2017), qualitatively and quantitatively, document and evaluate this progress and show how the power sector results are in reasonable agreement with detailed power and energy system models. In principle, IAMs rely on a parameterization of such detailed models when representing the challenges and options of wind and solar PV integration. The REMIND model is parameterized for a broad range of system configurations with the help of two detailed models: DIMES (Ueckerdt et al., 2017) and REMIX (Scholz et al., 2017).

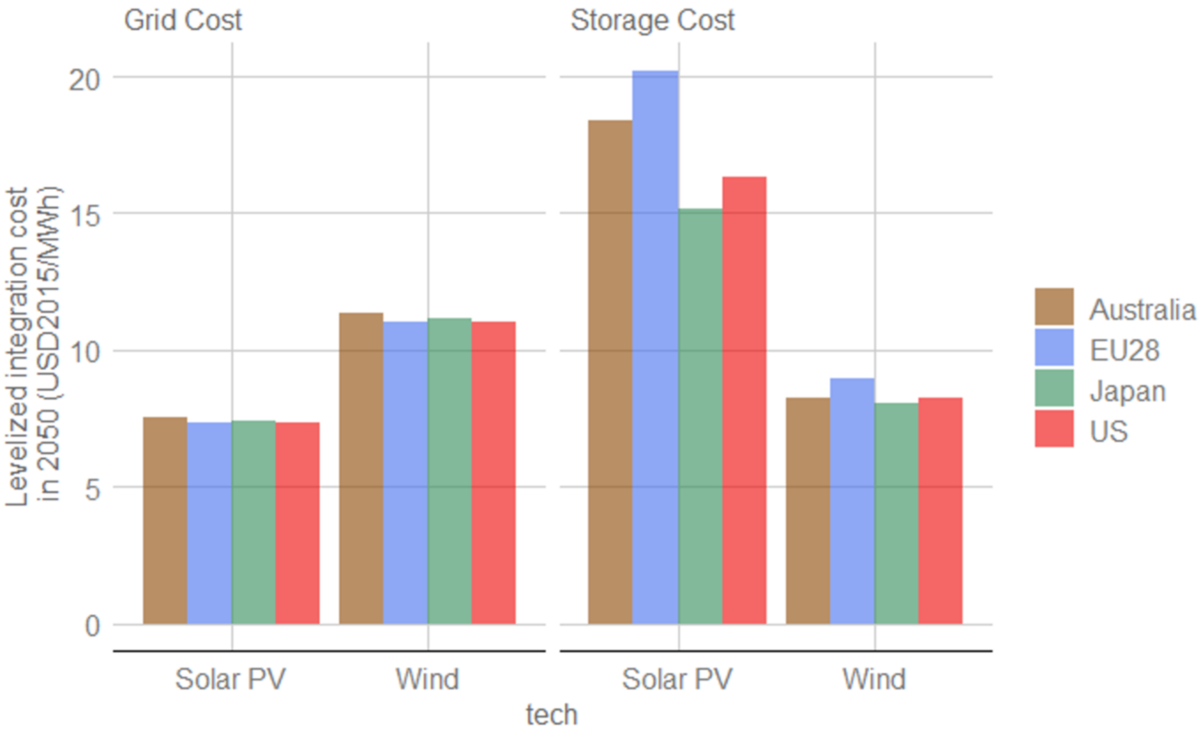
What are the key insights of detailed power and energy system models (ESMs) regarding the integration of high shares of variable renewables (VRE)? There is an ever-increasing number of modeling studies that explore the technical and economic feasibility of a 100% renewable power system. A recent review (Hansen et al., 2019) assesses 180 peer-reviewed articles, while another review in (Ringkjøb et al., 2018) compare the methodology of 75 ESMs that model high VRE shares. There is a broad consensus a 100% renewable electricity supply is technically feasible and economically viable, while some references present doubts (e.g. Clack et al., 2017; Heard et al., 2017), which were mostly debunked (Brown et al., 2018). The most comprehensive review (Hansen et al., 2019) includes numerous studies of 100% renewable system also for the three regions that reach close to 100% renewable power systems in our IAM study.

Finally, Suppl. Figures 6 to 8 provide insight into the VRE integration in our model. They show the *Net-zero Nuc. out* scenario which is the most challenging for VRE integration since it features full VRE potentials but no nuclear power. In particular, battery capacities, hydrogen turbines and gas turbines provide sufficient peak capacity (and system adequacy) as well as flexibility to the grid. The amount of dispatchable (i.e. non-variable) capacities (including batteries, gas turbines, hydrogen turbines, hydropower) is always larger than peak demand in the 2050 power systems (Suppl. Fig. 6). The integration of high shares of VRE electricity incurs three types of cost: cost of storage, cost of additional grid expansion and cost due to curtailment of VRE electricity that cannot be provided to the grid at certain hours of the year. In our Net-zero scenario, storage and grid cost in 2050 per unit wind and solar electricity add to additional cost of about 20 USD/MWh (Suppl. Fig 8). After taking into account generation losses by curtailment of about 10% (wind) and 15% (solar PV), VRE electricity remains competitive against other low-carbon options (Suppl. Fig 12, see LCOE in Suppl. Fig 7).

Suppl. Figure 6: Power sector capacities in 2050 of the Net-zero Nuc. out scenario and estimated peak electricity demand across the four regions.



Suppl. Figure 7: Curtailment rate (share of curtailed electricity) of wind and solar PV in the Net-zero Nuc. out scenario across the four regions.

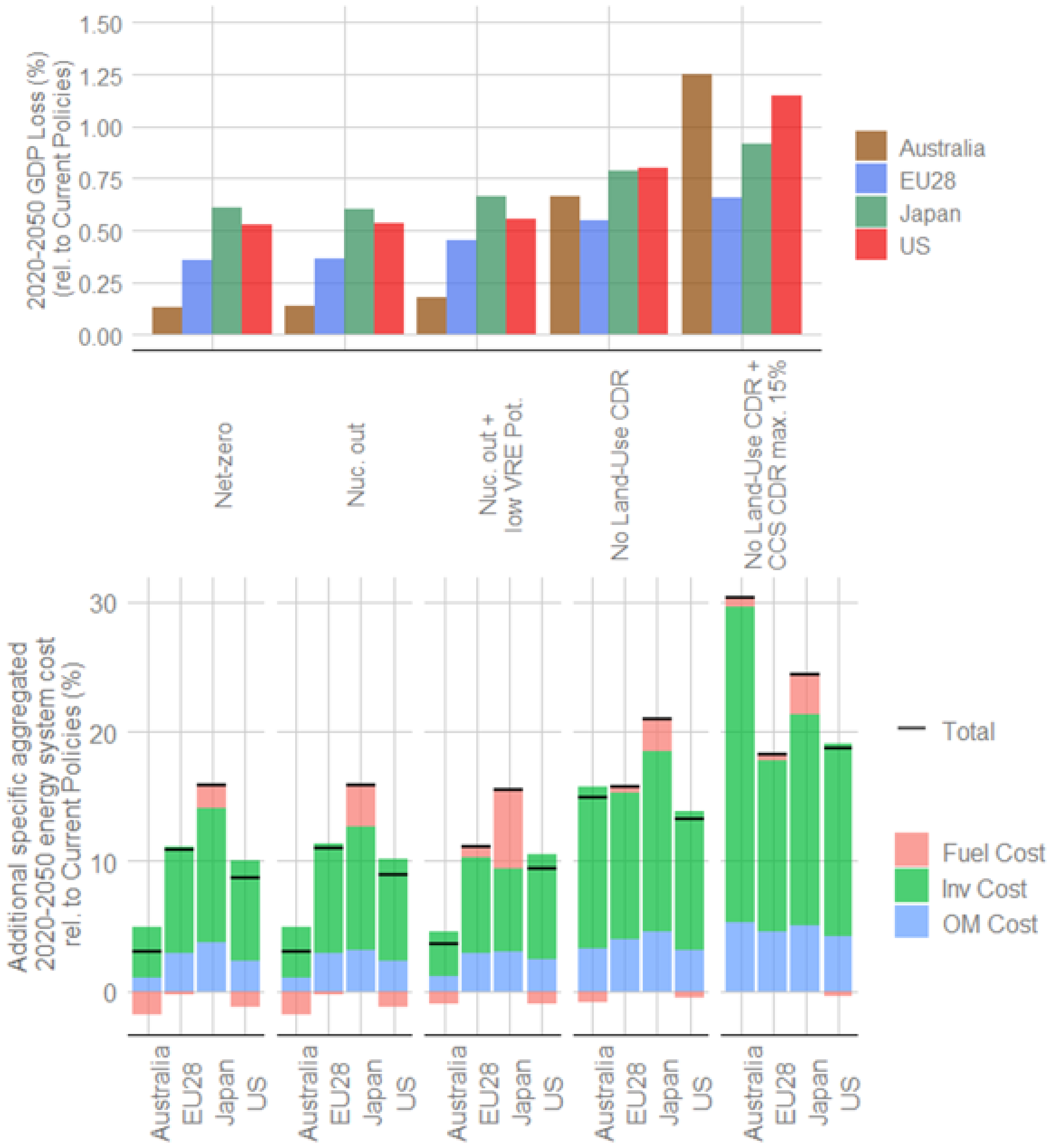


Suppl. Figure 8: Levelized integration cost of building of storage and grid expansion for solar PV and wind generation in 2050 across the four regions in the Net-zero Nuc. out scenario. These are additional system costs calculated per generation unit of wind and solar PV. Adding generation costs (LCOE) and integration costs (as was done for Suppl. Fig. 12) gives a new metric of system LCOE which is a more adequate comparison for power generation technologies (Ueckerdt et al., 2013).

S8. Other cost metrics

In addition to the metric of carbon and electricity prices (main text), here we present two more cost metrics, which are common in integrated assessment modeling: GDP losses and total energy system cost. We investigate these additional metrics again for the default net-zero scenario and the sensitivity scenarios.

GDP losses are calculated as the relative difference in 2020-2050 aggregated and discounted (5%/yr) GDP between the respective scenario and the Current Policies scenario. Energy system cost are calculated as follows: We sum total investment, operation and maintenance cost and the cost of primary energy fuel used domestically. We aggregate and discount those over 2020-2050 (as for GDP). Next, we divide by the aggregate 2020-2050 final energy consumption to obtain a specific measure which removes the effect that total energy system cost are only smaller because less energy needs to be provided in this region. We then compute the relative difference to the Current Policies scenario in terms of these specific aggregate energy system cost.



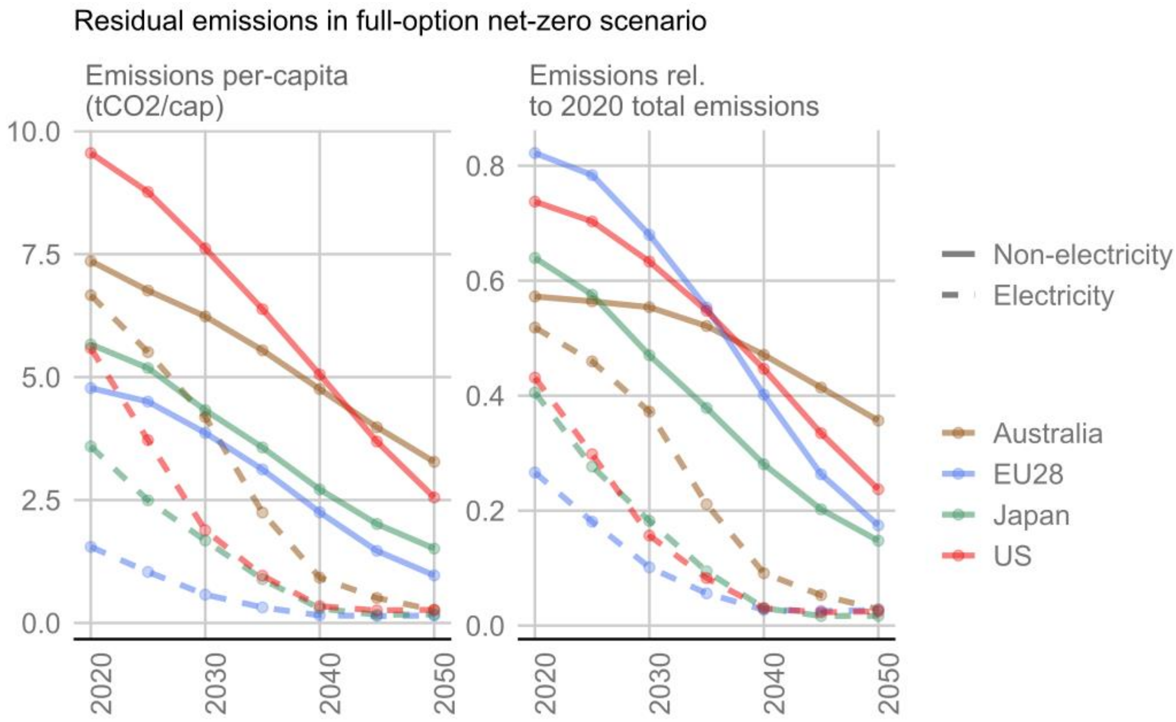
Suppl. Figure 9: GDP losses (top panel) and energy system cost (bottom panel) across the five net-zero scenarios and four regions. Both metrics are calculated as relative differences to the Current Policies scenario. The difference in energy system cost is moreover disentangled into three components: investment cost (Inv Cost), operation and maintenance cost (OM Cost) and fuel cost.

These cost metrics are more complex and more difficult to interpret than the ones in the main text. Carbon prices and electricity generation cost can be derived from shadow prices of model constraints in a specific year and for a specific scenario. GDP losses and additional energy system cost on the other hand are aggregated measures and depend on relative differences to a reference scenario (here: Current Policies). Interpreting them requires disentangling regional differences from scenario differences.

GDP losses remain similar across the power sector sensitivity scenarios with only a slight increase in the limited VRE scenario in Japan and the EU (Suppl. Fig 9, top). In turn, Australia and US face the largest cost increases in terms of GDP in the limited CDR scenarios. Regarding energy system cost, a typical feature of decarbonization scenarios is that investment and operation and maintenance cost increase, while fuel cost remain similar of even decrease (Suppl. Fig 9, bottom). This is due to the shift to renewable energy which is more capital-intensive but requires less primary energy fuel. Across the power sector sensitivity scenarios, there is no significant increase in energy system cost, yet we observe a shift from investment cost to fuel cost in the EU and Japan due to the decrease in VRE electricity share. A significant increase in energy system cost can be seen in the limited CDR scenarios, in particular, in Australia and the US, which is related to the enhanced use of bioenergy for demand-side decarbonization.

The fact that 2020-2050 aggregate GDP losses and energy system cost do not significantly increase in the net-zero scenario with constrained power sector options and increased electricity generation cost suggests that the additional cost are small in an economy-wide picture. However, this does not reflect the societal importance of electricity price as a key indicator that partly determines the acceptance towards an energy transition. In addition, our model currently underestimates the importance of the electricity sector to some extent as some options of power sector coupling (electrification) are not yet represented (deep electrification of transport and industry as well as the option to produce green hydrogen-based synthetic fuels, which require large amounts of electricity). This could significantly alter the impact of increased electricity prices in a system or economy-wide picture. These features are currently under development in REMIND and will be part of the technology portfolio in future studies.

S9. Residual CO2 emissions in standard net-zero scenario: electricity and non-electricity



Suppl. Figure 10: Residual (gross) CO2 emissions from the electricity sector (dashed lines) and from non-electric energy use (thick line) across the four regions in the Net-zero scenario in per-capita terms (left) and relative to total 2020 emissions (right). The relative 2020 values do not add up to one since they are normed by total net emissions and all regions have some negative land-use change emissions by 2020.

S10. Nuclear power assumptions in Japan

As nuclear power is a crucial but controversial option for Japan, we report modeling assumptions in more detail here. Suppl. Table 2 provides an overview of Japanese nuclear power capacity in 2050 in the full-option net-zero scenario and the cost assumptions for nuclear power in Japan.

Variable	**Unit**	**Value**
Nuclear power capacity in 2050 in full-option net-zero scenario (Fig. 3a)	GW	32
Nuclear power capital cost	US$2015/kW	5488 by 2020, increasing to 6982 by 2050
Nuclear power plant lifetime	years	40
Nuclear power plant capacity factor after 2035	share	0.8

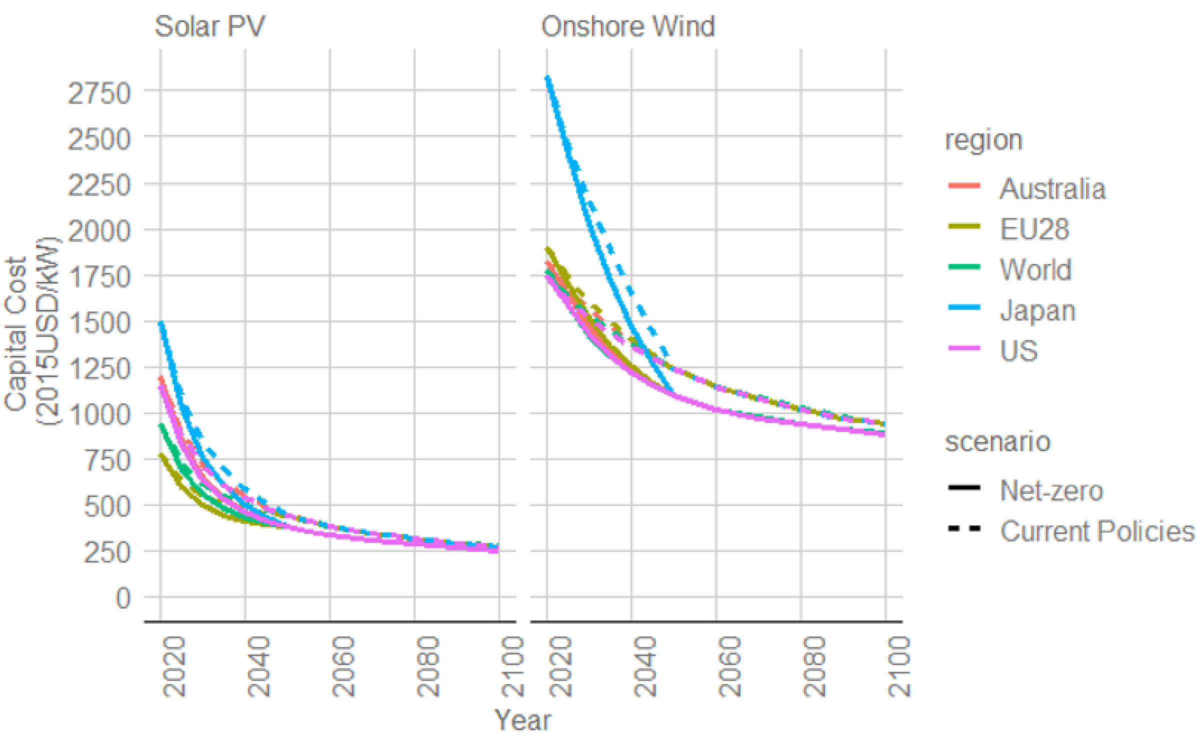
Suppl. Table 2: Nuclear power capacity in Japan by 2050 in the full-option net-zero scenario, nuclear capital cost in 2020 and 2050, plant lifetime and plant capacity factor.

S11. Drivers of electricity generation cost

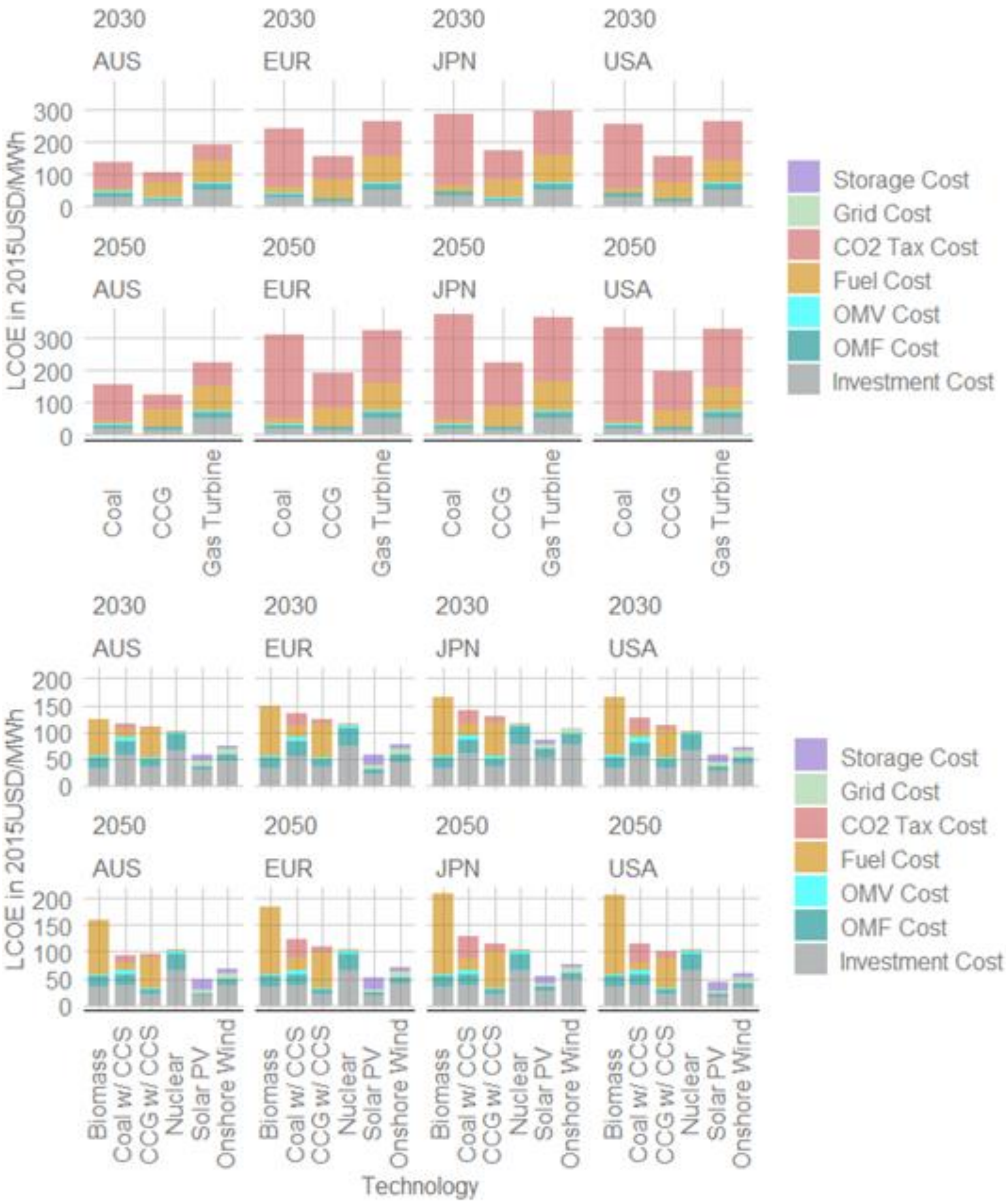
This section provides a summary of the drivers of electricity generation cost in our Net-zero scenario. While a very comprehensive comparison of techno-economic parameters to other IAMs was given for an earlier version of REMIND by Krey et al. (2019). Here we report on some important parameter changes and comparative metrics from our Net-zero scenario to improve the understanding of our power sector results.

An important feature of the model is *endogenous learning* about VRE technologies where we lowered the floor cost of solar PV and wind compared to earlier model versions (used in Krey et al.). The capital cost trajectories resulting in the Net-zero scenario can be seen in Suppl Fig. 11. Moreover, average capacity factors of new solar PV and wind plants from the Net-zero scenario can be found in Suppl. Table 3.

Finally, Suppl. Fig. 12 presents Levelized Cost of Electricity (LCOE) for key power sector technologies of REMIND2.1.2 for 2030 and 2050 in the Net-zero scenario. Note that this represent a post-processing estimate based on techno-economic parameters and output from the model and is not an exact representation of how the model optimizes. The main dynamics are captured by investment cost, operation and maintenance cost, fuel cost and cost related to the carbon price as well as integration cost. However, other cost components that the model takes into account like the cost of CO2 storage, the cost of curtailment or the additional benefit of providing flexibility to the grid (as in the case of gas turbines) are not included here.



Suppl. Figure 11: Capital cost trajectories of the standard Net-zero and Current Policies scenarios for solar PV and onshore wind plants in USD/kW. Regional values for the four regions as well as the global average are shown.

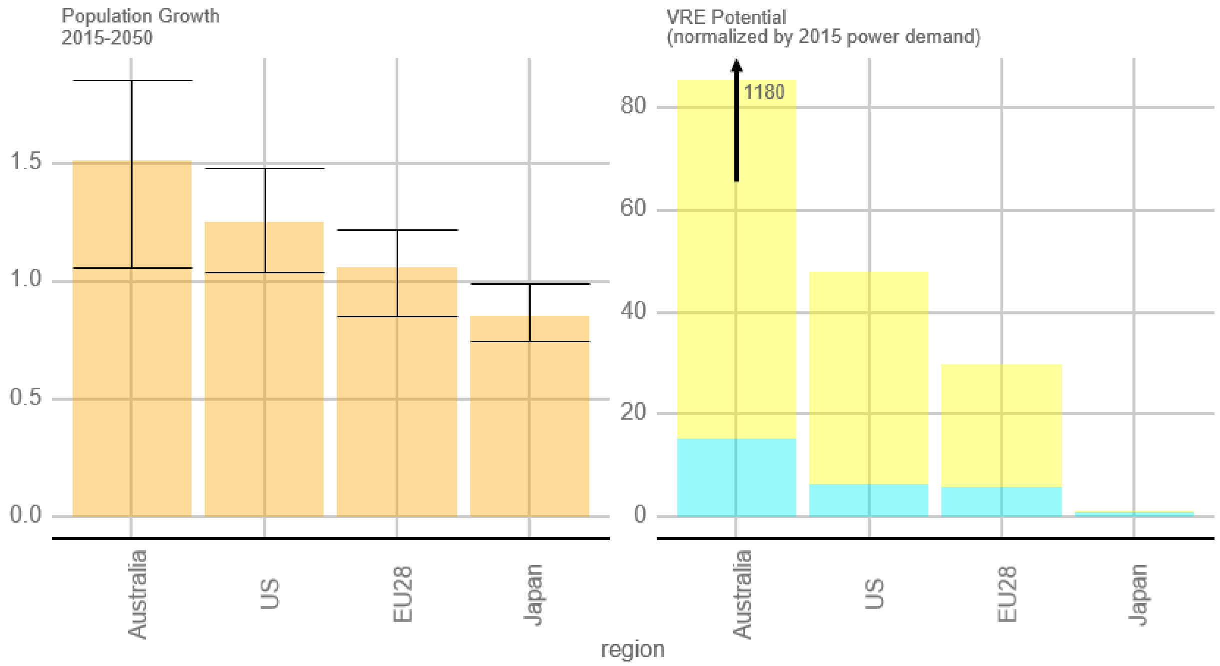


Suppl. Figure 12: Levelized cost of electricity (LCOE) for main fossil (top panel) and low-carbon (bottom panel) technologies by 2030 and 2050 in the Net-zero scenario in 2015USD/MWh(el).

Average Capacity Factor of New VRE Plants		**2030**	**2050**
Solar PV	Australia	19%	18%
	EU	18%	17%
	US	20%	19%
	Japan	12%	12%
Onshore Wind	Australia	29%	25%
	EU	30%	23%
	US	31%	31%
	Japan	24%	20%

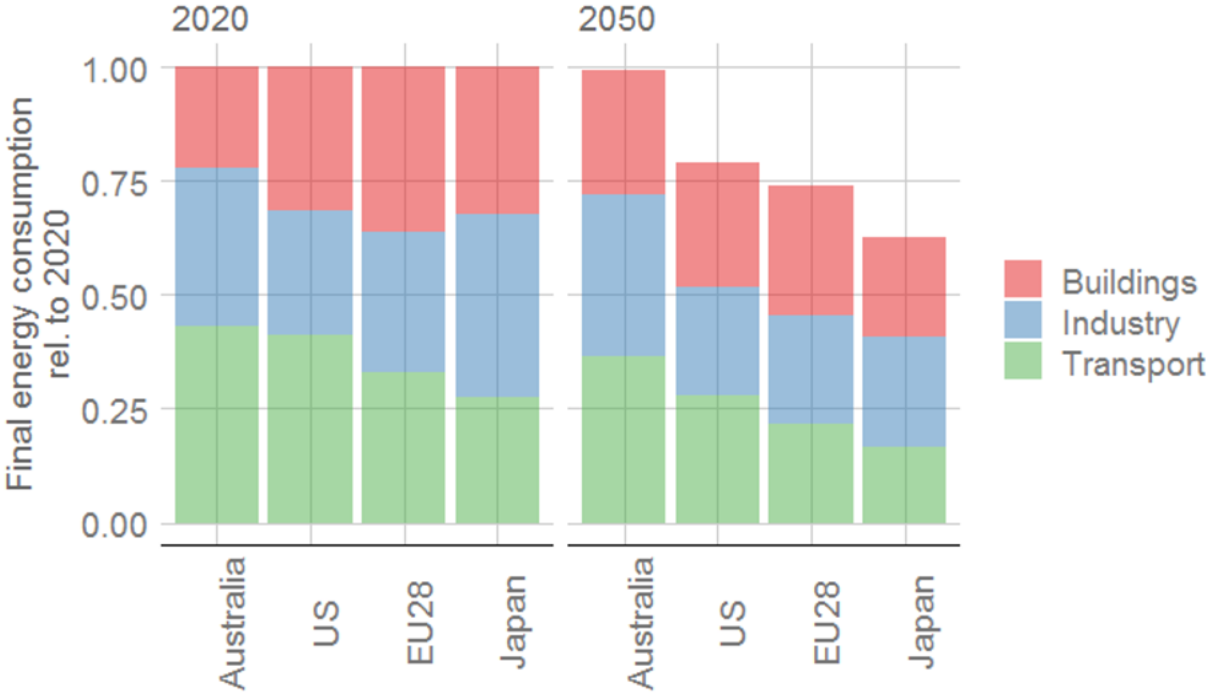
Suppl. Table 3: Average capacity factor of new VRE plants in the (standard) Net-zero scenario in 2030 and 2050. Marginal capacity factors of the first VRE plants in the best locations are higher than these average values.

S12. Modeling assumptions on population trends and VRE potential



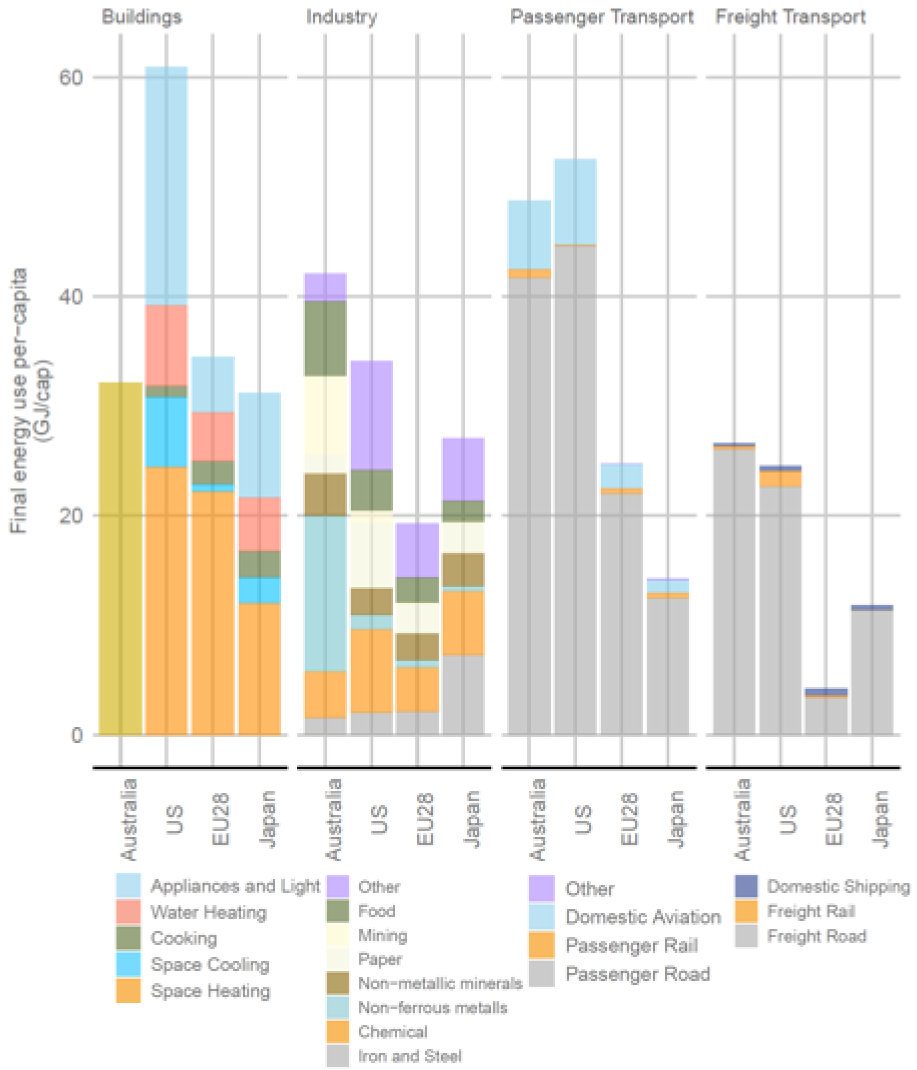
Suppl. Figure 13: Population change between 2015 and 2050 in the SSP2 scenario assumed in this study and VRE Potentials normalized by power demand in 2015 across the four regions. The error bars in the right panel show the range of the other SSP population scenarios (SSP1-SSP5). The arrow above the Australian VRE potential indicates that the potential is even higher (1180 times the power demand) and was cut off for the illustration.

S13. Energy demand trends 2020-2050 in the Net-zero scenario



Suppl. Fig. 14: Final energy consumption across sectors in 2020 and 2050 relative to 2020 in the Net-zero scenario.

S14. Current per-capita final energy consumption across sectors

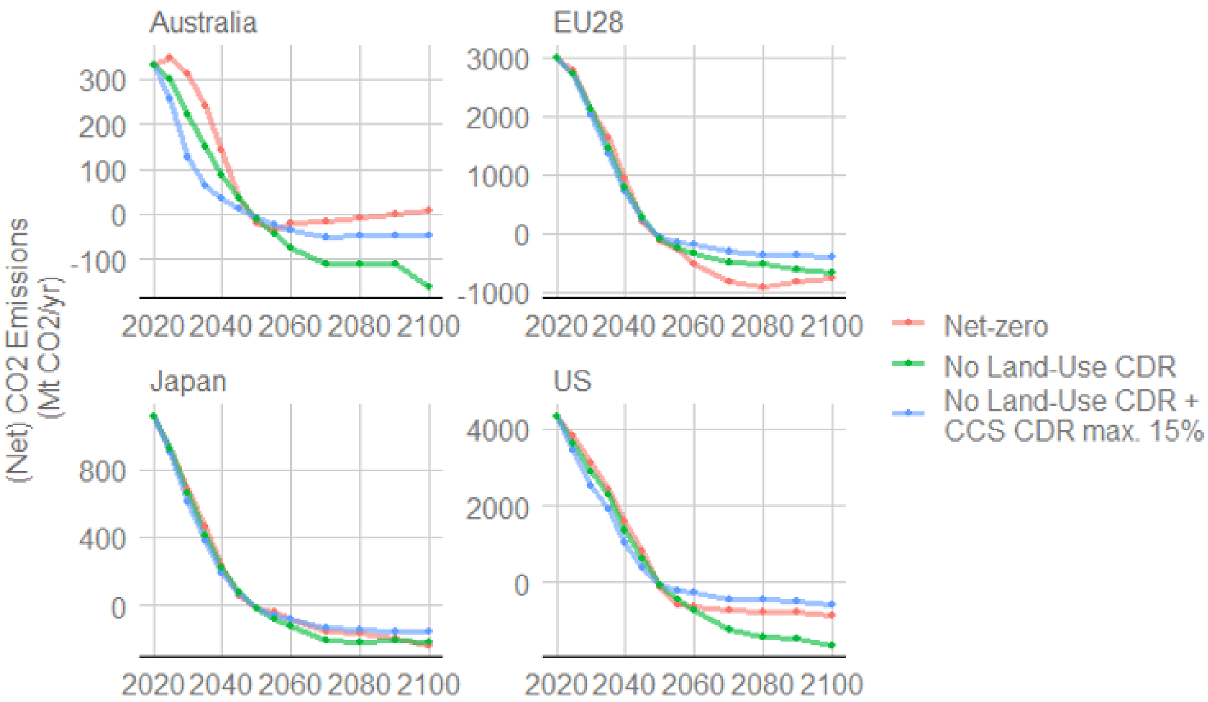


Suppl. Figure 15: Historic (2015 for industry and buildings, 2010 for transport) final energy consumption across sectors, subsectors and regions. Data on end-uses in the Australian buildings sector were not available and only the totals of residential and commercial energy use from IEA (2017) are shown. The remaining buildings data are from Levesque et al. (2018), industry data from IEA (2017) and transport data from Rottoli et al. (under review).

S15. Long-term emission trajectories and the role of CDR

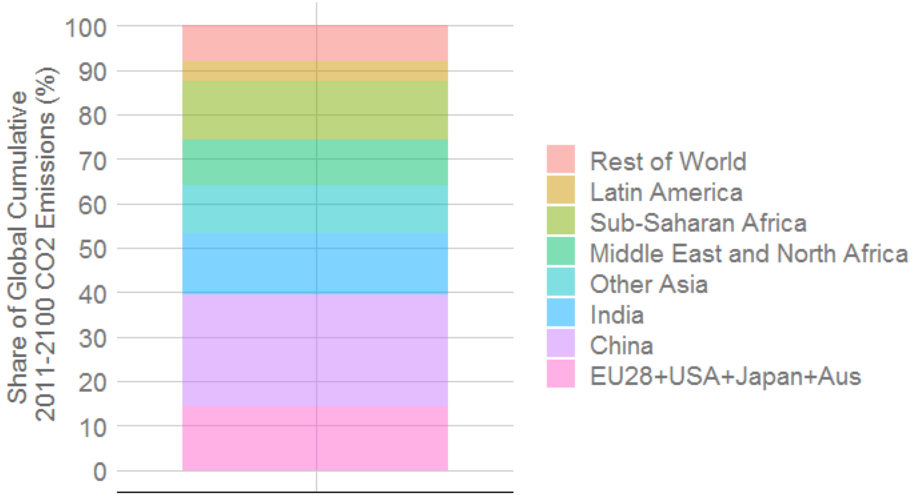
Suppl. Figure 16 shows the CO2 emission trajectories of the Net-zero and the two CDR sensitivity scenarios up to 2100. Achieving net-zero by 2050, regions will likely go for net negative emissions in the second half of the century for two reasons. First, the CDR capacities that have been built up to 2050 remain in place and are being used beyond 2050, while residual CO2 emissions further decrease due to an ongoing transformation (see the 2050 trend of residual emissions in Suppl. Figure 10). The net-zero targets imposed in our study leads to earlier deployment of CDR compared to a scenario that reaches global warming targets with only a uniform carbon price. Second, there is still an incentive contribute (net) emission reductions to global climate mitigation given that corresponding international frameworks remain in place to reward this. In our scenarios, the carbon price increases after 2050 also in the four industrialized economies from their respective regional level in 2050, although at a lower rate (see Suppl. Fig 3). This then incentivizes additional mitigation and potentially additional CDR.

The extent to which regions realize net negative emission in our scenarios depends on two factors: carbon price level and CDR potential. Australia, for instance, realizes less net negative emissions in the default Net-zero scenario than in the limited CDR scenarios due to a low carbon price incentive (as in the default scenario it could reach net-zero with a relatively low carbon price trajectory). Yet, it also depends on the socio-technological availability of CDR options and in case of the EU, for instance, CDR limitations reduce net negative emissions despite higher carbon prices.



Suppl. Figure 16: CO2 emission trajectories of the standard Net-zero and the two CDR sensitivity scenarios up to 2100. Note that the dynamics after 2050 are still governed by an increasing carbon price trajectory (see Suppl. Fig 3) providing incentive for net negative emissions if possible.

S16. Regional Distribution of 2011-2100 CO2 2°C Budget in Net-zero Scenario



Suppl. Figure 17: Regional share of cumulative 2011-2100 CO2 emissions in the Net-zero scenario (from total 1300 Gt CO2).

S17. Decomposition of abatement into mitigation strategies

We use the following method to attribute emission abatement between the *Current Policies* scenario (reference) and the *Net-zero* scenario to different mitigation strategies. The variables used for the disaggregation are:

$E, E_{el}, E_{nonel}, E_{tf}$: total net CO2 emissions, gross electricity CO2 emissions, gross non-electricity CO2 emissions, transport fuel CO2 emissions

$FE, FE_{t,el}$: final energy consumption, final energy electricity in transport

α: electricity share in FE,

E_{luc}: net CO2 emissions from land-use change,

CDR_{BECCS}, CDR_{DACCS}: carbon dioxide removal from BECCS/DACCS (positive values reflect net removals to the atmosphere).

Net emissions sum up as:

$$E = E_{el} + E_{nonel} + E_{luc} - CDR_{BECCS} - CDR_{DACCS}.$$

Furthermore, we define different (gross) carbon intensities:

$CI = (E_{el} + E_{nonel})/FE$ (carbon intensity of energy),

$CI_{el} = E_{el}/(\alpha FE)$ (carbon intensity of electricity),

$CI_{nonel} = E_{nonel}/\big((1-\alpha)FE\big)$ (carbon intensity of non-electricity).

The attribution of total abatement between the reference scenario (subscript 1) and the net-zero scenario (subscript 2) is based on an assumption of the order in which mitigation strategies are applied. While in the model all variables are changed at the same time, this method is based on changing only one variable at a time, which makes it necessary to define an order. The following order reflects our assumption of the cost of the mitigation strategies where low-cost strategies like energy efficiency gains and electricity sector transition come before electrification, non-electricity decarbonization and CDR.

First, we calculate the abatement from the energy efficiency gain of transport electrification EFG that is reflected in our model:

$$EFG = 2\,(FE_{t,el,2} - FE_{t,el,1})CI_{tf,1}.$$

Our model assumes that across all transport modes replacing transport fuels with electricity increases energy efficiency by a factor of three. Replacing transport fuels with electricity thus saves emissions of two units of transport fuels per unit of electricity added only by efficiency gains. Second, we assume that energy demand reduction, which is largely driven by energy efficiency gains, is the first mitigation strategy applied and contributes an abatement of the final reduction across the two scenarios multiplied by the carbon intensity of the reference scenario. In addition, we subtract the energy efficiency gain from electrification as this is attributed to electrification later:

$$EDR = (FE_1 - FE_2)\,CI_1 - EFG.$$

Next, we calculate the abatement contribution of the electricity sector decarbonization by:

$$ELD = \alpha_1 FE_2\big(CI_{el,1} - CI_{el,2}\big).$$

Here, we assume that final energy has already been reduced by the first strategy to FE_2, while we still have the electrification rate of the reference scenario α_1. The abatement contribution of electrification is calculated as

$$ELF = (\alpha_2 - \alpha_1)FE_2(CI_{nonel,1} - CI_{el,2}) + EFG.$$

This is the abatement contribution of replacing non-electric energy by electric energy including energy efficiency gains. Subsequently, residual gross energy abatement is attributed to the category non-electricity decarbonization by

$$NED = FE_2(1 - \alpha_2)(CI_{nonel,1} - CI_{nonel,2}).$$

Finally, land-use change abatement and carbo dioxide removal (CDR) account for the remaining difference in total net CO2 emissions:

$$LUCDR = (E_{luc,1} - CDR_{BECCS,1} - CDR_{DACCS,1}) - (E_{luc,2} - CDR_{BECCS,2} - CDR_{DACCS,2}).$$

It is possible to show that the disaggregation is complete and sums up to the total net abatement:

$$E_1 - E_2 = EDR + ELD + ELF + NED + LUCDR.$$

S18. Scenarios from IAMC database used in Figure 1

The following scenarios from the IAMC database were used to generate the right panel in Figure 1:

Scenario	Model
ADVANCE_2020_Med2C	AIM/CGE 2.0
ADVANCE_2020_Med2C	IMAGE 3.0.1
ADVANCE_2020_Med2C	MESSAGE-GLOBIOM 1.0
ADVANCE_2020_Med2C	POLES ADVANCE
ADVANCE_2020_Med2C	REMIND 1.7
ADVANCE_2020_Med2C	WITCH-GLOBIOM 4.2
ADVANCE_2020_WB2C	AIM/CGE 2.0
ADVANCE_2020_WB2C	IMAGE 3.0.1
ADVANCE_2020_WB2C	MESSAGE-GLOBIOM 1.0
ADVANCE_2020_WB2C	POLES ADVANCE
ADVANCE_2020_WB2C	REMIND 1.7
ADVANCE_2020_WB2C	WITCH-GLOBIOM 4.2
ADVANCE_2030_Med2C	AIM/CGE 2.0
ADVANCE_2030_Med2C	IMAGE 3.0.1
ADVANCE_2030_Med2C	MESSAGE-GLOBIOM 1.0
ADVANCE_2030_Med2C	POLES ADVANCE
ADVANCE_2030_Med2C	REMIND 1.7
ADVANCE_2030_Med2C	WITCH-GLOBIOM 4.2
ADVANCE_2030_Price1.5C	AIM/CGE 2.0
ADVANCE_2030_Price1.5C	MESSAGE-GLOBIOM 1.0
ADVANCE_2030_Price1.5C	POLES ADVANCE
ADVANCE_2030_Price1.5C	REMIND 1.7
ADVANCE_2030_Price1.5C	WITCH-GLOBIOM 4.2
ADVANCE_2030_WB2C	AIM/CGE 2.0
ADVANCE_2030_WB2C	IMAGE 3.0.1
ADVANCE_2030_WB2C	MESSAGE-GLOBIOM 1.0
ADVANCE_2030_WB2C	POLES ADVANCE
ADVANCE_2030_WB2C	REMIND 1.7
ADVANCE_2030_WB2C	WITCH-GLOBIOM 4.2
CD-LINKS_NPi2020_1000	AIM/CGE 2.1
CD-LINKS_NPi2020_1000	IMAGE 3.0.1
CD-LINKS_NPi2020_1000	MESSAGEix-GLOBIOM 1.0
CD-LINKS_NPi2020_1000	REMIND-MAgPIE 1.7-3.0
CD-LINKS_NPi2020_1000	WITCH-GLOBIOM 4.4
CD-LINKS_NPi2020_1600	AIM/CGE 2.1
CD-LINKS_NPi2020_1600	IMAGE 3.0.1
CD-LINKS_NPi2020_1600	MESSAGEix-GLOBIOM 1.0

CD-LINKS_NPi2020_1600	REMIND-MAgPIE 1.7-3.0
CD-LINKS_NPi2020_1600	WITCH-GLOBIOM 4.4
EMF33_1.5C_cost100	REMIND-MAgPIE 1.7-3.0
EMF33_1.5C_full	REMIND-MAgPIE 1.7-3.0
EMF33_1.5C_nofuel	REMIND-MAgPIE 1.7-3.0
EMF33_Med2C_cost100	AIM/CGE 2.1
EMF33_Med2C_cost100	MESSAGE-GLOBIOM 1.0
EMF33_Med2C_cost100	REMIND-MAgPIE 1.7-3.0
EMF33_Med2C_full	AIM/CGE 2.1
EMF33_Med2C_full	MESSAGE-GLOBIOM 1.0
EMF33_Med2C_full	REMIND-MAgPIE 1.7-3.0
EMF33_Med2C_limbio	MESSAGE-GLOBIOM 1.0
EMF33_Med2C_limbio	REMIND-MAgPIE 1.7-3.0
EMF33_Med2C_nobeccs	AIM/CGE 2.1
EMF33_Med2C_nobeccs	MESSAGE-GLOBIOM 1.0
EMF33_Med2C_nobeccs	REMIND-MAgPIE 1.7-3.0
EMF33_Med2C_nofuel	AIM/CGE 2.1
EMF33_Med2C_nofuel	MESSAGE-GLOBIOM 1.0
EMF33_Med2C_nofuel	REMIND-MAgPIE 1.7-3.0
EMF33_Med2C_none	AIM/CGE 2.1
EMF33_Med2C_none	MESSAGE-GLOBIOM 1.0
EMF33_Med2C_none	REMIND-MAgPIE 1.7-3.0
EMF33_tax_hi_full	AIM/CGE 2.1
EMF33_tax_hi_full	IMAGE 3.0.2
EMF33_tax_hi_full	MESSAGE-GLOBIOM 1.0
EMF33_tax_hi_full	REMIND-MAgPIE 1.7-3.0
EMF33_tax_hi_none	MESSAGE-GLOBIOM 1.0
EMF33_WB2C_cost100	AIM/CGE 2.1
EMF33_WB2C_cost100	IMAGE 3.0.2
EMF33_WB2C_cost100	MESSAGE-GLOBIOM 1.0
EMF33_WB2C_cost100	REMIND-MAgPIE 1.7-3.0
EMF33_WB2C_full	AIM/CGE 2.1
EMF33_WB2C_full	IMAGE 3.0.2
EMF33_WB2C_full	MESSAGE-GLOBIOM 1.0
EMF33_WB2C_full	REMIND-MAgPIE 1.7-3.0
EMF33_WB2C_limbio	IMAGE 3.0.2
EMF33_WB2C_limbio	MESSAGE-GLOBIOM 1.0
EMF33_WB2C_limbio	REMIND-MAgPIE 1.7-3.0
EMF33_WB2C_nobeccs	IMAGE 3.0.2
EMF33_WB2C_nobeccs	REMIND-MAgPIE 1.7-3.0
EMF33_WB2C_nofuel	IMAGE 3.0.2
EMF33_WB2C_nofuel	MESSAGE-GLOBIOM 1.0
EMF33_WB2C_nofuel	REMIND-MAgPIE 1.7-3.0
EMF33_WB2C_none	REMIND-MAgPIE 1.7-3.0

Suppl. Table 3: Models and scenarios used in Figure 1 from the IAMC SR15 database (Huppmann et al., 2018).

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