

Article

It Is Still Possible to Achieve the Paris Climate Agreement: Regional, Sectoral, and Land-Use Pathways

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Abstract: It is still possible to comply with the Paris Climate Agreement to maintain a global temperature ‘well below +2.0 °C’ above pre-industrial levels. We present two global non-overshoot pathways (+2.0 °C and +1.5 °C) with regional decarbonization targets for the four primary energy sectors—power, heating, transportation, and industry—in 5-year steps to 2050. We use normative scenarios to illustrate the effects of efficiency measures and renewable energy use, describe the roles of increased electrification of the final energy demand and synthetic fuels, and quantify the resulting electricity load increases for 72 sub-regions. Non-energy scenarios include a phase-out of net emissions from agriculture, forestry, and other land uses, reductions in non-carbon greenhouse gases, and land restoration to scale up atmospheric CO₂ removal, estimated at −377 Gt CO₂ to 2100. An estimate of the COVID-19 effects on the global energy demand is included and a sensitivity analysis describes the impacts if implementation is delayed by 5, 7, or 10 years, which would significantly reduce the likelihood of achieving the 1.5 °C goal. The analysis applies a model network consisting of energy system, power system, transport, land-use, and climate models.

Keywords: climate change; Paris Agreement; 100% renewable energy; 1.5 °C mitigation pathway; energy transition; energy scenario; GHG mitigation; CO₂ emission; non-energy emission; open access book

1. Introduction

Given the challenge that climate change poses for the global community, our research is dedicated to solutions for a low-emission society. To reach a net zero emission society in 2050, we develop normative emission pathways for a temperature rise well below 2 °C. Across various research disciplines, this scenario analysis combines climate, energy, transport, and land use models for a comprehensive picture of the tasks at hand, linking fossil energy emissions to non-energy-related GHG sources and sinks. We depict transition strategies for 100% renewable energy system in all 10 world regions, providing information of the necessary infrastructure, new capacity and investment, which would enable efforts by governments and society to keep climate change well below 2 °C and therefore in line with the Paris Climate Agreement. Earlier results of this research have been presented at Long-term-Scenarios for the Energy Transition (LTES) events [1].

Many scenarios have already been constructed and analysed to guide both policy and investment in limiting climate change ‘by keeping global temperature rise this century well below 2 degrees Celsius above pre-industrial levels’, according to the 2015 Paris Climate Agreement [2]. These published long-term scenarios [3–6] agree that the rapid decarbonization of energy production is required, together with significant negative emissions, throughout the 21st century. Many scenarios rely heavily upon nuclear power and natural-gas- or coal-fired power with carbon capture and storage (CCS) to decarbonize energy production, and negative emissions achieved with bio-energy with carbon capture and storage (BECCS). The 5th Assessment Report (5 AR) and the Special Report on Global Warming of 1.5 °C (SR 1.5) of the Intergovernmental Panel on Climate Change (IPCC) also include a large number of representative concentration pathways (RCPs) illustrating a wide range of mitigation strategies [7,8].

Quantitative scenarios are usually constructed with modelling approaches, but always follow explicit or implicit ‘if-then’ narratives, which should never be understood as future predictions. In the global energy and emission pathways developed and discussed here, we use a storyline-and-modelling approach to make consistent assumptions about the implementation of technologies and to accommodate the multidimensional and multi-perspective character of the decision-making processes. Our intention is to increase the plausibility of the scenarios, rather than to identify supposedly cost-optimal solutions based on uncertain cost assumptions. With this approach, we develop narratives that target a society with net-zero CO₂ emissions by 2050 and construct exemplary normative scenarios that focus on the mitigation of CO₂ in the energy, agriculture, and land-use sectors.

These narratives represent a complementary basis for the difficult political and social decision-making processes required for the comprehensive decarbonization of energy systems. In contrast to previous studies, we have identified the technology paths that are suitable and necessary to achieve the decarbonization of the global energy system, with improvements in efficiency and 100% renewable energies only, by 2050. Limiting possible technologies and avoiding technical carbon dioxide removal (CDR) techniques are justified by the high potential utility of renewable energies and their low specific costs compared with those of nuclear and fossil power plants coupled to CCS and BECCS [9]. Moreover, the environmental effects and social acceptance of the latter options are highly contentious [10]: specifically, the unresolved disposal of radioactive waste in the case of nuclear power [11], and the unresolved doubts about the long-term effectiveness of underground storage of CO₂ in the case of CCS [12].

Therefore, the 2 °C and 1.5 °C scenarios presented here are ‘non-overshoot’ scenarios that use only widespread and publicly accepted technologies to generate renewable energies or produce green synthetic fuels. The scenarios also fulfil society’s obligation to reduce its current energy-related emissions and limit the future energy demand. They meet the overall energy-related CO₂ emission budget of only 590 and 450 gigatonnes of CO₂ (Gt CO₂) respectively between 2015 and 2050, and also consider the non-CO₂ emissions and natural carbon sinks when estimating the overall greenhouse gas (GHG) emissions and related temperature increases. Most of the published 1.5 °C (low) overshoot pathways [13] include negative emission technologies, which buffer the heavy burden of energy transition in some way.

The pathways presented in this paper build upon a recently published scenario study [14]. The detailed assumptions, including technology and cost data, and the results tables can be found in the Supplementary Materials. Both pathways are considered to achieve targets ‘well below 2.0 °C’, with one representing the upper limit (2.0 °C Scenario) and one the lower limit (1.5 °C Scenario). The ‘reference’ (REF) scenario (5.0 °C Scenario) is based on the *Current Policies Scenario* published by the International Energy Agency (IEA) [15]. Using a comprehensive emissions accounting system, the pathways for the four major energy sectors—power, heat, transport, and industry—are based on GHG-mitigation strategies for 10 world regions, and focus on the distribution and consumption of energy and related emissions are the main driver of climate change [16]. The increased electri-

fication of transport and heating systems, in order to replace fossil fuels with renewable electricity, plays an important role in those scenarios. The underlying solar and wind potentials were derived from a Geographic Information System (GIS)-based analysis of the required land area to avoid conflicts with other land uses, such as for natural carbon sinks (forests). To further investigate the use of installed capacities in the power systems, the system was modelled at high regional and temporal resolutions. Therefore, the 10 world regions were subdivided into 72 sub-regions to analyse their load developments and storage demands. Atmospheric GHG concentrations and radiative forcing, and their implications for global mean temperature and sea-level rises, were also analysed. To define a sustainable pathway for land-use change and the agricultural sector, we combined the investigation of future energy systems with measures for negative emissions provided by well-established natural land restoration methods. We used reduced-complexity carbon cycle and climate modelling to assess the climatic effects of the calculated emissions pathways. The analysis thus applies an integrated model network consisting of energy systems, power systems, transport, land use, and climate models.

2. Results and Discussion

2.1. Development of Energy Demand Intensities

Starting from the REF scenario, narratives for the demand side of the normative scenarios were developed. The main drivers of the final energy demand in the scenarios are population growth and economic development. The world's population is expected to grow from 7.4 billion in 2015 to 9.8 billion by 2050 [17]. It is assumed that the world's gross domestic product (GDP) will increase, on average, by 3.2% per year in the next three decades [15]. Therefore, our scenarios are based on improvements in efficiency and resulting reductions in demand (Table 1). The implementation of technical efficiency measures plays a significant role in the 1.5 °C Scenario, particularly before 2030. However, both the 1.5 °C and 2.0 °C Scenarios differ only slightly in their final annual energy demands in 2050. In both cases, efficiency measures are required to decouple economic growth and final energy consumption. Conversion losses are reduced, particularly by replacing thermal power generation with renewable technologies. This further reduces the primary energy intensity. The REF Scenario provides the lower benchmarks for efficiency potentials derived from the Current Policies Scenario of the IEA World Energy Outlook [15]. The upper benchmarks for the efficiency potentials for each world region are taken from the literature [18,19], including the low-energy-demand (LED) scenario [20,21]. In the transport sector, a combination of technical measures and modal shifts reduce annual passenger kilometres for private vehicles by 25% in OECD countries under the 1.5 °C scenario. The shift towards electric mobility might be driven by vehicle emission standards and economic incentives to phase out internal combustion engines. It is expected that the acquisition costs for electric cars will be similar to those for cars with combustion engines during the next decade and that maintenance costs will become increasingly competitive.

Table 1. Main strategies and narratives for all regions in each sector of the energy system for the 2.0 °C and 1.5 °C Scenarios compared with the Reference Scenario.

Sector	Main Strategies and Narratives with Different Regional Emphases and Characteristics	Global Average sectoral Demand Intensity	
Industry electricity	Implementation of more-efficient appliances, especially electric drives for compressed air, pumps, fans, and other cross-sectional technologies.	kWh/USD1000 GDP 2015: 55 2050 REF: 36 2050 2.0 °C: 24 2050 1.5 °C: 23	
Industry heating	Electrification of industrial heat will increase from 6% to 34% in 2050 in the 2.0 °C Scenario and to 37% in the 1.5 °C Scenario. Technological improvements, process substitutions, and innovations will be encouraged by favourable conditions and regulative frameworks, allowing rapid technological changes. Integration of waste heat into processes will reduce losses.	MJ/USD1000 GDP 2015: 690 2050 REF: 366 2050 2.0 °C: 185 2050 1.5 °C: 172	
Other sectors (*) electricity	Electricity demand intensities in households, for commercial purposes, and in the service and trade sectors, fisheries, and agriculture will be reduced by the use of most-efficient technologies for lighting, information, communication, cooking, cooling, and hot water. Compared with the REF case, a reduction in specific consumption (depending on region, a slower increase resp.) is assumed for the 1.5 °C pathway over the medium term, as long as fossil power generation dominates.	kWh/USD1000 GDP 2015: 78 2050 REF: 60 2050 2.0 °C: 38 2050 1.5 °C: 37	kWh/capita 2015: 1350 2050 REF: 2370 2050 2.0 °C: 1500 2050 1.5 °C: 1460
Other sectors (*) heating	Share of electric heating will rise from 5% in 2015 to 30% in 2050 in the 2.0 °C Scenario and to 37% in the 1.5 °C Scenario. Final energy use for heating will be reduced and switching heating to low-temperature technologies, such as heat pumps and floor heating. These measures are supplemented with responsible consumption behavior by the consumer, especially in the 1.5 °C Scenario.	MJ/USD1000 GDP 2015: 700 2050 REF: 300 2050 2.0 °C: 180 2050 1.5 °C: 170	MJ/head 2015: 12,600 2050 REF: 11,700 2050 2.0 °C: 7300 2050 1.5 °C: 6700
Transport	Main strategies include electrification and synthetic fuels (hydrogen and synthetic liquid hydrocarbons), depending on the transportation mode. Mode shifts from road and air to more-efficient rail and bus will reduce the share of energy-intensive motorized private transport. Efficiency gains for engines and a moderate use of biofuels will also help to achieve rapid and strong emissions reductions.	MJ/USD1000 GDP 2015: 760 2050 REF: 380 2050 2.0 °C: 130 2050 1.5 °C: 100	MJ/head 2015: 13,000 2050 REF: 15,000 2050 2.0 °C: 5100 2050 1.5 °C: 3900

Narratives are similar in all regions, whereas the demand intensities differ significantly—for both the base year 2015 and the end of the modelling period in 2050. (*) Other Sectors include buildings (residential, commercial, and public services) and the agricultural, forestry, and fishing sectors.

2.2. Demand and Supply Pathways towards +2 °C and +1.5 °C Targets

The role of energy efficiency in decarbonization scenarios is widely documented. The IPCC [8] concluded that ‘at the global level, scenarios reaching about 450 ppm CO₂eq are (also) characterized by more rapid improvements in energy efficiency’ and Lovins [22] identified energy efficiency among the most cost-effective ways to reduce carbon emissions. As well as reducing the energy demand by improving energy efficiency, the two energy decarbonization pathways are based on expanding renewable energy supply technologies [21]. Figure 1 shows the resulting final energy demands by sector and scenario, and the primary energy by energy carrier. The measures documented in Table 1 will reduce the total final energy demand to below 280 EJ in 2050 compared with around 540 EJ in the 5 °C (REF) case. Accordingly, annual global primary energy use decreases from 556 EJ in 2015 to about 440 EJ by 2050 under the 2.0 °C Scenario and to 412 EJ under the 1.5 °C Scenario. Both scenarios are non-overshoot scenarios with no CDR technologies, so a rapid reduction in fossil fuels and a significant deployment of renewable energies would already be necessary by 2025. Solar and wind power are the backbones of such an energy system, with complementary contributions from hydro, biomass, and geothermal energy (Figure 1). Compared with today, the installation of renewables-based power and heat generation technologies accelerates significantly.

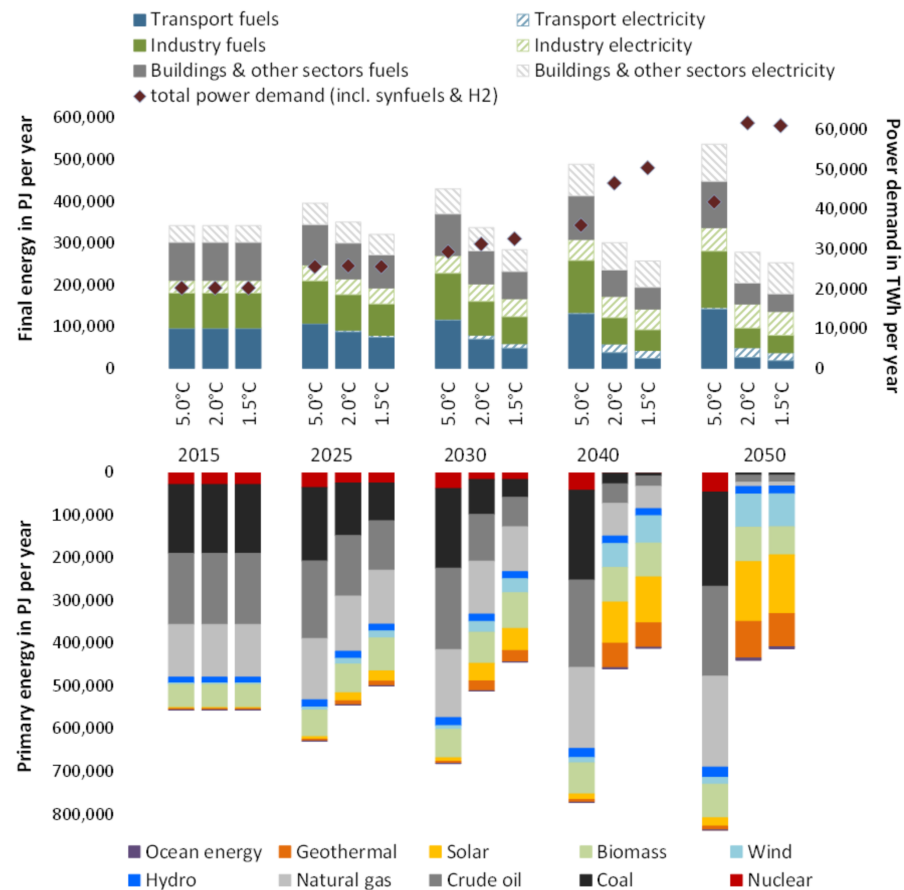


Figure 1. Final energy demand per sector, gross power demand (upper panel), and primary energy supply, including non-energy use (bottom panel), in the scenarios.

Transformation of the Transport Sector

An increase in the efficiency of vehicles with internal combustion engines and a direct electrification rate of 50% by 2050 on world average (Table 2) would be necessary to decrease the final energy consumption of the transport sector by more than 60%, as required for the 2 °C Scenario.

Table 2. Proportions of the final sectoral energy demands met by electricity under the 1.5 °C Scenario. Colors indicate the different electrification shares where red is lower and green is higher.

		2015	2020	2025	2030	2035	2040	2045	2050
DEMAND Transport Electricity Share [%]	OECD North America	0%	0%	5%	18%	35%	45%	51%	54%
	Latin America	0%	0%	2%	9%	36%	48%	53%	53%
	OECD Europe	0%	0%	6%	35%	57%	67%	65%	65%
	Africa	0%	0%	1%	3%	12%	19%	25%	31%
	Middle East	0%	0%	1%	4%	21%	32%	38%	41%
	Eurasia	0%	1%	3%	13%	39%	44%	47%	46%
	Non-OECD Asia	0%	0%	3%	10%	29%	35%	37%	37%
	India	0%	1%	5%	22%	47%	58%	57%	57%
	China	4%	4%	10%	29%	52%	62%	60%	60%
	OECD Pacific	0%	0%	8%	33%	58%	61%	62%	63%
	Global average	1%	1%	5%	17%	38%	46%	49%	50%
DEMAND Industry Electricity Share [%]	OECD North America	29%	28%	28%	32%	40%	49%	51%	55%
	Latin America	23%	23%	25%	29%	33%	40%	47%	56%
	OECD Europe	35%	35%	36%	39%	43%	46%	48%	51%
	Africa	26%	25%	26%	30%	36%	42%	47%	52%
	Middle East	9%	10%	12%	16%	22%	30%	36%	44%
	Eurasia	23%	24%	23%	30%	35%	40%	43%	45%
	Non-OECD Asia	24%	25%	25%	31%	37%	40%	45%	49%
	India	18%	20%	21%	29%	38%	48%	54%	56%
	China	26%	29%	32%	38%	47%	55%	58%	61%
	OECD Pacific	35%	36%	36%	41%	46%	50%	53%	56%
	Global average	26%	27%	28%	33%	40%	47%	51%	54%
DEMAND Buildings Electricity Share [%]	OECD North America	50%	49%	50%	55%	57%	58%	60%	61%
	Latin America	38%	40%	44%	48%	55%	62%	69%	76%
	OECD Europe	31%	33%	34%	38%	47%	49%	51%	53%
	Africa	8%	8%	11%	15%	22%	32%	40%	49%
	Middle East	43%	46%	48%	51%	54%	59%	68%	75%
	Eurasia	18%	19%	20%	23%	26%	28%	31%	35%
	Non-OECD Asia	22%	24%	25%	31%	40%	48%	56%	61%
	India	17%	19%	26%	34%	43%	55%	61%	69%
	China	24%	27%	32%	41%	53%	58%	63%	66%
	OECD Pacific	52%	53%	54%	55%	56%	62%	63%	64%
	Global average	30%	31%	33%	38%	45%	50%	55%	60%

Table 2. Cont.

		2015	2020	2025	2030	2035	2040	2045	2050
GENERATION Renewable Electricity Share [%]	OECD North America	10%	12%	35%	65%	86%	96%	99%	100%
	Latin America	33%	39%	53%	67%	84%	96%	100%	100%
	OECD Europe	17%	20%	34%	56%	71%	87%	95%	100%
	Africa	58%	57%	62%	68%	79%	90%	99%	100%
	Middle East	1%	4%	13%	27%	54%	79%	99%	100%
	Eurasia	6%	9%	21%	41%	62%	79%	91%	100%
	Non-OECD Asia	32%	31%	43%	62%	77%	86%	95%	100%
	India	36%	33%	46%	65%	82%	91%	97%	100%
	China	12%	16%	29%	49%	70%	83%	93%	100%
	OECD Pacific	6%	11%	25%	49%	71%	85%	94%	100%
	Global average	18%	21%	35%	56%	74%	88%	96%	100%

An even steeper reduction in the transport demand and more-drastic efficiency-improvement measures (electrification, modal shifts) are required under the 1.5 °C Scenario. In this scenario, the energy demand of the global transport sector is 74% lower in 2050 than under the 5 °C Scenario. Electrification of the vehicle stock and altering transport modes to reduce energy-intensive transport activities will have a high decarbonization effect. However, measures such as the expansion of public transport and the vehicle-sharing infrastructure are equally important. The direct electrification of air and ship transport is particularly limited, so under the 2.0 °C and 1.5 °C Scenarios, electricity-based synthetic fuels increasingly replace fossil fuels in these sectors.

2.3. Regional Differences

How much each renewable energy source supplies to the total demand depends on regional opportunities for and constraints upon deploying renewable energies [21,23]. In the 1.5 °C Scenario, solar heat and power technologies provide over 50% of the total primary energy demand in the global sun belt, because solar is readily available and comparatively inexpensive (see Figure 2). The Middle East exemplifies the solar region model. With low biomass and hydro resources, the Middle East will rely on the development of dispatchable technologies, such as hydrogen production or concentrated solar power, which will help to store the abundance of solar energy. In contrast, in Europe and Eurasia, with their long cold winters, solar contribute only ~20%. Latin America represents a ‘bioenergy and hydro region’, where biomass provides easily accessible heat and hydro provides dispatchable (balancing) power. A previous detailed analysis for Brazil [24] supports this approach.

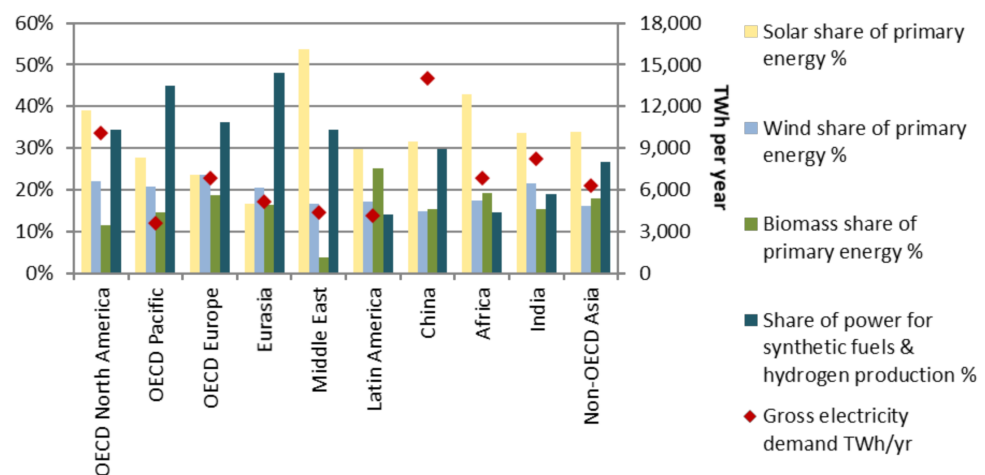


Figure 2. Selected regional characteristics of energy demand and supply in the 1.5 °C Scenario in 2050.

Synthetic fuels, including hydrogen, will become increasingly relevant under the carbon constraint when the share of renewables exceeds 80% (Figure 2). The option to store and distribute energy carriers (hydrogen or synthetic fuels) will be important in this case, especially in regions in which both solar and biomass resources are limited. Eurasia would dedicate almost 50% of its power production for this purpose in the 1.5 °C Scenario. China has the highest power production of all regions in our 1.5 °C Scenario, and would require around 4000 TWh per year in 2050 to generate synthetic gases and fuels to balance the variable renewables, to provide off-season power, and to indirectly electrify the process heat and transport sectors. This large power demand is a special challenge. Recent studies have shown that the regionally integrated deployment of renewable technologies can technically manage this transition, even for the eastern demand centres [25,26]. Because of its industrial lifestyle, North America already has a high proportion of electrification and a large power demand. Therefore, it will also require large amounts of synthetic fuels in our

1.5 °C Scenario. India is another key region for global development and will rely strongly on solar energy for its transformation. In contrast to the various regional requirements for solar, biomass, and synthetic fuels, wind would provide a stable share of 15%–20% in all regions, even under quite different regional assumptions for the synthetic fuel demand.

2.4. Sector Coupling—Electrification Replaces Thermal Processes

Electrification is a key to replacing fossil fuels in thermal processes and combustion engines in all sectors under both high-renewables scenarios. Electrification shares of over 50% of final energy by 2050 (Table 2) will rely on a rapid increase from 21% in 2015 to 38% by 2030, significantly increasing the interactions and interdependencies between power production and power consumption and storage in the transport, industry, and building sectors (Figure 3). As a consequence, the global annual electricity demand increases by 13,600 TWh between 2015 and 2035 and by 7890 TWh between 2035 and 2050 under the 1.5 °C Scenario. Therefore, fossil-fuel-based power generation would be replaced by renewables-based generation, increasing the latter by a factor of 7 between 2015 and 2035. By 2050, ~62,300 TWh per year would be generated from renewables under the 1.5 °C Scenario. This is also required to substantially supply the transport sector. The proportion of electricity in the total final energy used by the transport sector in 2015 was less than 1%, although the proportion was markedly higher in China at 4%, nearly half of which was attributable to the rail system and half to 2- and 3-wheeler vehicles and buses. Under the 1.5 °C Scenario, 38% of the final global transport energy demand needs to be electrified by 2035, although this varies greatly between regions. The industry and building sectors need to double their electrification rates, for both space and process heat, to meet the scenario targets.

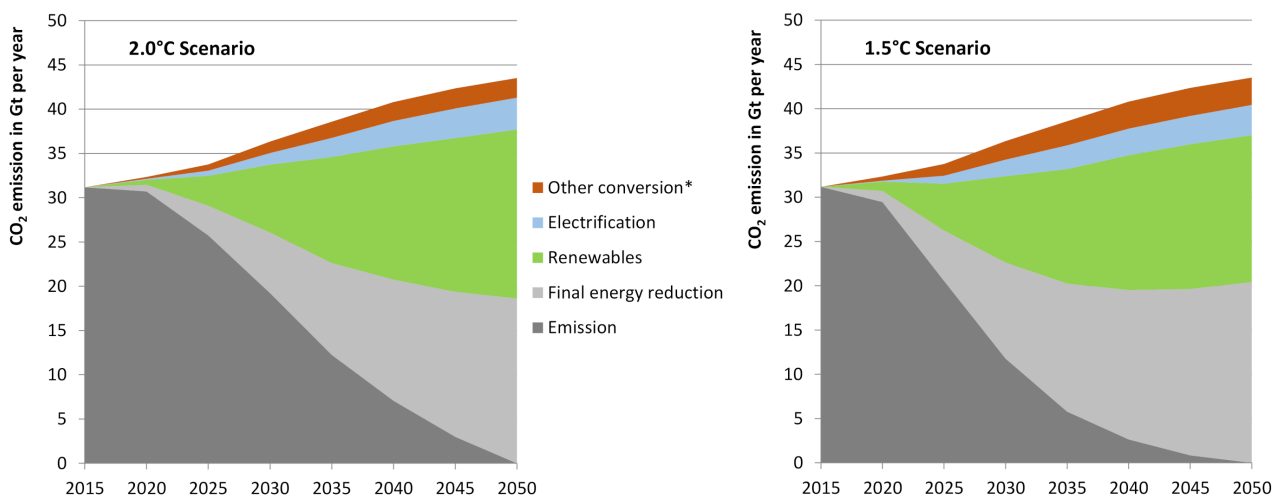


Figure 3. Annual CO₂ emissions reductions in the 2.0 °C (left) and 1.5 °C Scenarios (right) in relation to the 5 °C (REF) Scenario according to the measures implemented. Renewable energies and efficiency measures (including efficiency improvements through electrification) are roughly equally important in all the scenarios. Reduced consumption has an even greater role in the 1.5 °C Scenario. Other conversions (*) include changes in district heating, refineries, coal transformation, and gas transport.

The pace of electrification will differ significantly between the regions. In our scenarios, China, Europe, and OECD Pacific are expected to take the lead in transport-sector electrification because environmental policy incentives are already emerging. In the building sector, electrification will be easiest for regions with low space-heat demands, in warmer climates. In areas with cold winters, such as Eurasia and Europe, investments in heat pumps are required to make electrification possible. Heat grids that integrate biomass, waste heat, and solar collectors are an efficient alternative, but both options require huge improvements in insulation to curb the energy demand. In sub-Saharan Africa, electrifica-

tion of the building and transport sectors are particularly challenging because the rates of electrification and urbanisation are low. However, recent observations indicate that there have been significant improvements in electrification in both rural and urban areas since 2014 [27].

2.5. Power Sector Analysis: Development of Electric Load and Storage Demand

Because electrification is a key transition strategy and wind and photovoltaic sources are highly volatile, we specifically focused on balancing the power systems with historic regional solar and wind data [28,29]. The modelling results show that the average loads increase in all 72 regions under both scenario alternatives. Under the 1.5 °C Scenario, the most significant increases and largest regional differences occur in Africa, where the average load increase between 480% in the northern regions and 750% in the southern regions, reflecting the significant regional differences in access to electricity and the electrification of the transport sector (Figure 4). In OECD Pacific, efficiency measures reduce the average load by 87% in 2030 compared to 2015. By 2050 however, load increases to 116%, as electric mobility and electric process heat in industry are added as new consumers. In most regions, the electrification and thus the load is expected to increase more under the stronger limitations of the 1.5 °C Scenario than in the 2.0 °C Scenario. Only if Middle East, India, and Non-OECD Asia leapfrog on efficiency measures, demand at the end of the modelling period can be leveled out. Flexibility measures, such as fast-reacting dispatch generation capacities and demand-side management, are used in our scenarios to reduce the need for additional transmission and storage capacities, but will not replace them entirely. Under the 2.0 °C Scenario, the global pumped hydro storage capacities increase by 6 GW and battery capacities by 0.8 GW annually between 2015 and 2030, to 244 GW and 12 GW, respectively. By 2050, pumped hydro will increase to 267 GW and batteries to 347 GW of the total installed capacity. By 2050, 197 GW of gas power plants and combined heat and power generation (CHP) capacity will either consume synthetic methane or be retrofitted for hydrogen use. In parallel, the average capacity factor for gas and hydrogen plants will decrease from 29% (around 2600 h/yr) in 2030 to 11% (just under 1000 h/yr) by 2050, providing dispatch power and ancillary services.

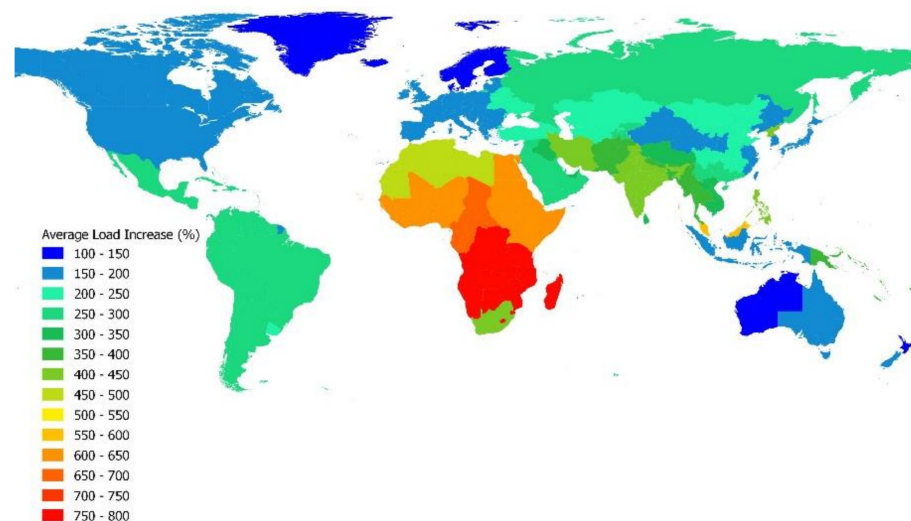


Figure 4. Increases in the average calculated load by 2050 in 72 regions under the 1.5 °C Scenario, in percentages relative to 2020. The average load was calculated across 8760 h per year. The regional ratios between the maximum and minimum loads vary significantly. ‘Residual load’ in this analysis is the load remaining after the generation of variable renewable power. Negative values indicate that the power generated from solar and wind exceeds the actual load and are exported to other regions, stored, or curtailed. The residual load varies significantly with increased variable generation because maximum load and maximum generation do not occur simultaneously.

2.6. Investment Required and Fuel Cost Savings

By 2050, electricity and synthetic fuels (including hydrogen) will supply 70% of the global final energy required in the 1.5 °C pathway. The overall cumulative investment in power generation required up to 2050 in our scenario is USD 51.1 trillion (USD 1.42 trillion annually on average), which is USD 30.7 trillion more than under the REF scenario, under which an investment of USD 20.4 trillion (USD 0.58 trillion annually) will be required. The overall fuel cost savings in the same scenario will add up to USD 28.8 trillion over the same period, or USD 0.8 trillion per year. Total fuel cost savings in the 1.5 °C pathway alone will cover 90% of the additionally necessary investments in renewable power generation in the 1.5 °C pathway.

The *levelized costs of electricity* (LCOE) of the global power sector under the REF Scenario (without including the costs of CO₂ emissions) are calculated to increase from USD 60 per MWh in 2015 to USD 79 per MWh in 2050. In comparison, the 2.0 °C Scenario will increase the generation costs to USD 77 per MWh by 2030, with a following reduction to USD 70 per MWh by 2050. Under the 1.5 °C Scenario, electricity generation costs will peak at USD 81 per MWh and decrease to USD 70 per MWh—equal to that in the 2.0 °C Scenario.

According to a recent market survey [9], the current LCOE is USD 192 per MWh for nuclear generation, USD 152 per MWh for coal-fired power generation, and USD 68 for gas-fired power (excluding CCS costs). As of 2019, there are two CCS facilities combined with power generation—the 115 MW coal-fired Boundary Dam plant in Canada [30] and the 240 MW gas-fired Petra Nova plant in the USA [31], at which CO₂ capture per tonne costs approximately USD 100 and USD 65, respectively, [32] although only a portion of all fugitive CO₂ emissions is captured. These are significantly higher than the cost of power generation from carbon-neutral renewables—USD 42 per MWh for utility-scale solar photovoltaic and USD 54 per MWh for onshore wind. The cost for sequestration with BECCS is approximately USD 100–200 per tonne CO₂ [33], and it has a limited mitigation potential of 1 Gt CO₂ per year [34]. In comparison, the cost of natural land restoration is <USD 100 per tonne CO₂, with an average potential of 7 Gt CO₂ per year [35,36].

2.7. Distribution of Carbon Emissions

We performed an ex-post analysis of the distribution of CO₂ emissions in the scenarios based on the technical transitions in the energy system. Compared with the IPCC RCPs, the pathways fall within the P1 category (IPCC SR1.5—P1 scenarios are defined as scenarios with lower energy demand up to 2050, due to innovations in social life, business, and technology. At the same time living standards increase and levelize. A leaner energy system facilitates rapid decarbonization of energy supply. Afforestation is the only CDR option considered; neither fossil fuels with CCS nor BECCS are used. OECD Pacific: Japan, South Korea, Australia, and New Zealand. The calculation of inter-regional exchange capacity requirements in MW is also possible, but beyond the scope of this article). Efficiency and electrification strategies strictly limit CO₂ emissions in both low temperature rise scenarios. The cumulative energy-related CO₂ emissions under the 5.0 °C Scenario between 2015 and 2050 are 1341 Gt CO₂, about three times higher than those under the 1.5 °C Scenario (449 Gt CO₂). The OECD regions, China, and India account for over 60% of all emissions under all scenarios, and the cumulative emissions of the combined OECD countries equal those of China. In the low-emission scenarios, the power sector dominates, accounting for one third of all cumulative energy-related carbon emissions, predominantly arising from the necessary phase-out times required for recently built fossil/coal-fired power plants. The industry and transport sectors follow, accounting for 20–25% each. The building/other sectors contribute 10% of carbon emissions under our scenarios. The carbon intensities for all sectors are shown in Table 3. The proportions of renewable electricity generated increase, leading to significant reductions in carbon intensity on the supply side, a prerequisite for low carbon intensities in all other sectors. Carbon emissions then plateau by 2025 and decrease thereafter in the 1.5 °C pathway.

Table 3. Carbon intensity by sector under the 1.5 °C Scenario. Carbon intensities for the industry, building, and transport sectors exclude the electricity consumed in these sectors. The prerequisites for reduced carbon intensity in the industry sector include infrastructural changes, such as renewables-based process heat generation technologies and co-generation. For the transport sector, infrastructural changes are required, such as charging networks for electric vehicles and the expansion of electricity-based public transport. The colour indicates the different carbon intensities by sector and region where red is high, yellow more average values and green low carbon intensity.

	t CO ₂ /PJ	2015	2020	2025	2030	2035	2040	2045	2050	
OECD North America	TRANSPORT	30,567	29,239	19,312	9134	2994	712	222	0	
Latin America		24,086	22,260	17,317	12,460	4682	319	5	0	
OECD Europe		21,353	20,018	15,026	5352	1563	18	0	0	
Africa		14,023	13,800	13,219	12,615	8969	5274	401	0	
Middle East		24,556	24,670	21,164	17,143	8102	2353	6	0	
Eurasia		12,571	12,695	11,301	8300	2861	11	6	0	
Other Non-OECD Asia		19,305	19,673	16,560	11,117	4322	1269	0	0	
India		11,297	12,300	10,587	5288	1765	513	0	0	
China		11,914	13,711	10,307	6964	2508	334	2	0	
OECD Pacific		22,475	20,662	13,432	6623	2007	445	0	0	
Global average		19,648	19,331	14,482	8878	3641	1057	75	0	
OECD North America		INDUSTRY	42,072	43,611	35,094	21,504	11,578	4247	853	0
Latin America			36,945	32,813	22,414	13,092	6328	2177	125	0
OECD Europe	40,393		38,716	32,526	23,713	16,861	10,115	3796	0	
Africa	37,228		35,765	28,767	17,582	10,537	3384	191	0	
Middle East	55,432		51,509	46,876	38,930	30,223	17,373	907	0	
Eurasia	44,482		42,274	29,360	19,198	14,782	9877	5000	0	
Non-OECD Asia	51,422		51,069	39,170	24,973	13,618	8979	3935	0	
India	52,443		51,840	40,147	24,769	11,766	6214	2782	0	
China	83,734		81,910	68,450	51,480	30,655	18,203	7727	0	
OECD Pacific	47,587		46,810	37,406	26,349	16,443	8356	3702	0	
Global average	58,941	56,882	46,116	32,117	18,837	10,485	3870	0		
OECD North America	BUILDINGS	28,813	28,158	19,287	10,353	3829	930	42	0	
Latin America		24,869	19,539	14,038	9339	5313	1371	167	0	
OECD Europe		32,810	30,840	23,200	13,997	9554	5002	1971	0	
Africa		8112	7962	6265	4499	2819	779	77	0	
Middle East		32,690	31,171	27,763	23,070	17,403	8489	313	0	
Eurasia		13,241	13,020	8139	3469	2812	1891	878	0	
Non-OECD Asia		19,648	19,331	14,482	8878	3641	1057	75	0	
India		16,926	14,363	9111	5303	1672	1235	640	0	
China		35,078	30,321	20,007	6094	4745	1242	269	0	
OECD Pacific		29,442	28,004	23,326	17,943	8146	4799	1509	0	
Global average	25,907	23,925	16,946	9702	5742	2462	631	0		

Table 3. Cont.

	t CO ₂ /PJ	2015	2020	2025	2030	2035	2040	2045	2050
OECD North America	POWER	139,196	125,786	50,187	14,120	5751	1577	119	0
Latin America		78,282	54,046	26,633	10,838	4470	1563	0	0
OECD Europe		97,367	73,323	40,254	22,912	16,018	7056	2608	0
Africa		204,093	173,995	109,773	52,020	16,706	2978	156	0
Middle East		213,418	203,593	144,467	86,342	22,917	5718	243	0
Eurasia		208,031	157,983	109,225	56,858	36,448	23,753	11,015	0
Non-OECD Asia		177,243	168,415	92,100	33,049	22,213	14,113	5417	0
India		279,508	234,522	116,945	52,299	21,537	3894	1473	0
China		142,179	115,016	77,626	34,766	8703	4726	2216	0
OECD Pacific		155,566	116,407	69,032	33,201	16,628	11,498	5344	0
Global average		150,579	127,401	74,485	34,763	14,788	6423	2353	0

2.8. Land-Use and Non-CO₂ Emission Mitigation Scenarios

2.8.1. Land-Sector Emissions

The land-sector emissions presented here are derived from a new probabilistic scenario based on four different land restoration pathways: reforestation, forest ecosystem restoration, sustainable use of forests, and agroforestry [37]. These pathways are based on the premise that the better management of terrestrial ecosystems, including the restoration of degraded natural ecosystems, will allow previously lost carbon stocks to be restored [38–40]. The global aggregated sequestration potential was calculated from the median values for an ensemble of draws for each sequestration pathway and climatic domain (temperate/boreal or tropical/sub-tropical), resulting in a theoretical potential of 151.9 Gt of carbon (C) by 2150 and a maximum carbon density cap of 377 Gt CO₂ to 2100 [41]. The four sequestration pathways were aggregated from country-level data for the five Representative Concentration Pathway (RCP) regions (Table 4), and can be considered to approximate biome-average sequestration rates if they are supported by specific land-use policies.

Table 4. Net carbon mitigation from land-use management pathways for 1.5 °C: 2020–2100.

Region [42]	Gt C/year	2020	2030	2040	2050	2060	2070	2080	2090	2100
Asia	LAND-USE	0.30	0.05	−0.32	−0.36	−0.35	−0.30	−0.25	−0.16	−0.10
Eastern Europe and Former Soviet Union (REF)		0.00	−0.13	−0.27	−0.28	−0.27	−0.26	−0.25	−0.22	−0.19
Middle East and Africa (MAF)		0.33	−0.19	−0.55	−0.57	−0.53	−0.42	−0.29	−0.14	−0.06
OECD 1990 Countries (OECD 90)		0.00	−0.18	−0.34	−0.34	−0.32	−0.28	−0.23	−0.18	−0.14
Latin America and Caribbean (LAM)		0.17	−0.27	−0.62	−0.62	−0.55	−0.42	−0.27	−0.14	−0.06
Annual global total		0.79	−0.81	−2.11	−2.17	−2.01	−1.68	−1.28	−0.84	−0.56
Cumulative global total		0.79	0.63	−15.35	−37.17	−58.20	−76.65	−91.18	−101.4	−108.25

Under the 1.5 °C pathway analysis [37], the effects of these different land-use options will sequester up to 32 Gt C by mid-century. The full extent of the net mitigation shown in Table 4 is required to achieve the 1.5 °C Scenario, whereas for the 2.0 °C Scenario, only a third of the sequestration potential is required. The 1.5 °C pathway is consistent with comparable scenarios in the literature [41], which showed mitigation rates of up to −2 Gt C per year from 2040 to 2050. The land-use-related emission and sequestration rates of the 2.0 °C and 1.5 °C pathways in the present study are within the range of currently published scenario distributions (CMIP6 CEDS and IPCC SR1.5 database [13]).

2.8.2. Non-CO₂ Emissions

Non-CO₂ emissions were modelled based on the other main GHGs (CH₄ and N₂O), fluorinated gases, and aerosols. The pathways for CH₄ and N₂O emissions were derived with a quantile regression method [37], resulting in long-term emission levels that track towards the lower end of the distributions of published scenarios (see above CMIP6 CEDS and IPCC SR1.5 database). They show a decline and plateau in CH₄ emissions and a slight increase in N₂O emissions over the course of the century, associated with agricultural activities [41]. Our quantile regression method assumes a phase out of halocarbon and fluorinated gases over the next 10–20 years, although it does not include the residual levels of background emissions [41]. In our 1.5 °C scenario, sulphate aerosol emissions are set below the SSP1 1.9 scenario, whereas NO_x emissions are between the levels in the SSP 1 2.6 and SSP 1 1.9 scenarios [41]. Emissions of black and organic carbon are not as low as those in the lower SSP scenarios because these emission sources correlate less strongly with fossil-fuel burning, and a reduction in both black and organic carbon emissions will offset the warming and cooling effects of each [41].

2.9. Sensitivity Analysis: The Risk of Delay and the Possible Impact of COVID-19

At the time of writing (June 2020), the COVID-19 pandemic had reduced the global energy demand in an unprecedented way. Initial projections for 2020 [43] estimate a drop in the global primary energy demand of 5%. The oil and coal demands are projected to decline by 8% each, in response to reduced transport services and industrial activities, respectively. Global gas consumption is anticipated to decrease by 4%. Overall energy-related CO₂ emissions are expected to fall by around 8% in 2020. If these forecasts come true, the global energy sector would be almost exactly on the 1.5 °C pathway in terms of the energy demand and overall fossil fuel consumption. Compared with the 1.5 °C Scenario assumptions for 2020, the actual use of coal in 2020 would be 3% lower and that of oil 2% lower, whereas the gas demand would still be 2% higher. However, the energy-related CO₂ emissions would still be 1.1 Gt above those required in the 1.5 °C pathway for 2020. In terms of the electricity-generating capacities from renewable energies, both solar photovoltaic and wind power are consistent with the 1.5 °C trajectory if the market volume for new installations of both technologies in 2019 (115 GW for photovoltaic and 60 GW for wind [44]) are maintained in 2020. However, these developments are being affected by the COVID 19 pandemic, and a short-term decline in technology expansion might be possible. The extent to which the pandemic and the subsequent efforts to revive the global economy can support long-term changes in policy or a restructuring of the global economy remains to be seen. Various socio-economic storylines assume that a rapid return to “business as usual” will prevail in many areas [45].

The delayed implementation of permanent measures that tend us towards the 1.5 °C pathway will lead to additional energy-related carbon emissions. In this analysis, we assume that the calculated CO₂ reduction pathways (2.0 °C and 1.5 °C) will begin 5, 7, or 10 years later than anticipated, and that emissions during that time will remain at the level of the year 2019. In this section, we quantify the additional cumulative carbon emissions that will result from these delays. The energy sector itself will be unable to compensate for those emissions, but will have to rely on society’s willingness to pay for net emission reduction technologies, such as BECCS and DACCS, and their inherent additional energy demands. Figure 5 shows the results (in billion metric tonnes) for the 10 world regions. If China delays the implementation of the 1.5 °C pathway by 5 years, an additional 45 billion tonnes of CO₂ will be released, more than the total annual global CO₂ emissions (33 billion tons) in 2019 [46]. The global CO₂ budget under the 1.5 °C Scenario (66% probability) will be surpassed by 13% if all OECD countries delay their decarbonization pathways by 5 years. The cumulative CO₂ emissions of China will equal those of all OECD countries, whereas those of India will equal those of OECD Pacific (OECD Pacific: Japan, South Korea, Australia, and New Zealand) (2015–2050, 1.5 °C scenario). Figure 5 shows the impact on global CO₂ emissions if a whole sector delays the implementation of the 1.5 °C decarbonization pathway. A 5-year delay by the power sector will result in 50 billion tonnes of additional CO₂ emissions.

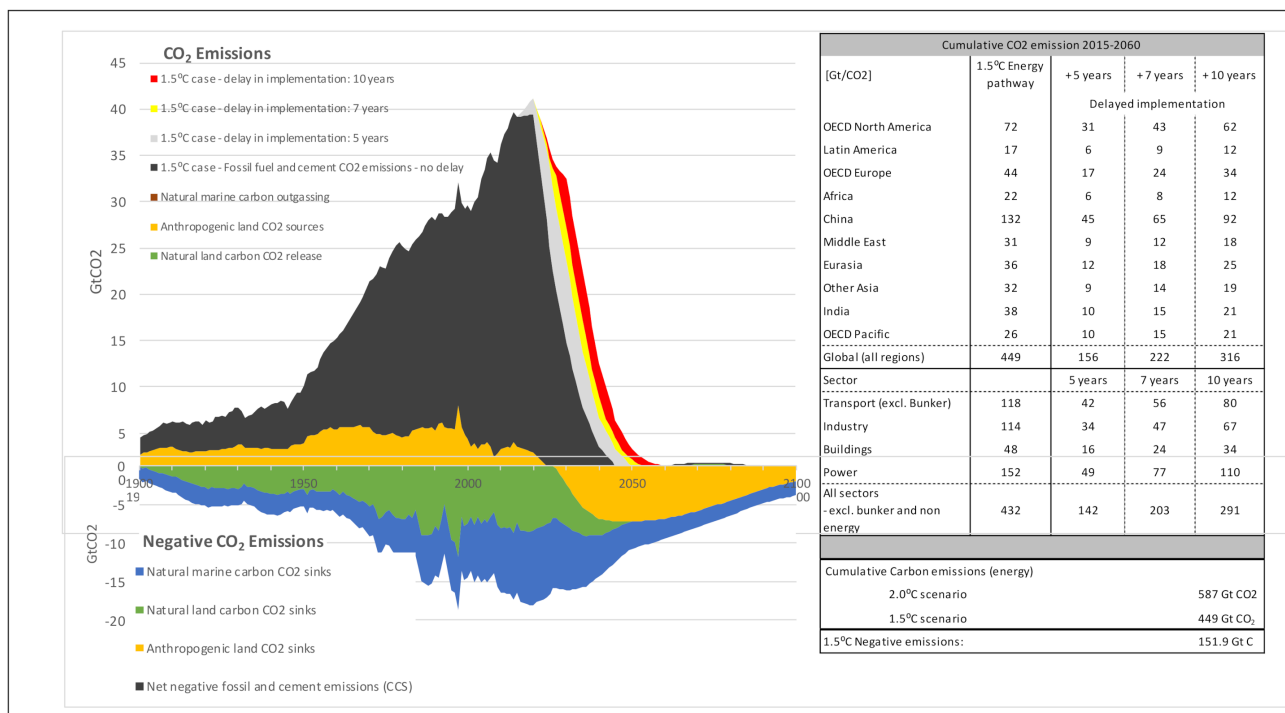


Figure 5. Annual and cumulative CO₂ emissions under the 1.5 °C Scenario by region and sector; additional cumulative CO₂ emissions if implementation is delayed (5, 7, or 10 years); and carbon sinks from land, oceans, and additional land restoration. Additional cumulative CO₂ emissions by region and sector were calculated on the assumption that CO₂ emissions will remain flat for this region and/or sector for the corresponding time period. Annual emissions are compared between the 1.5 °C pathway and the delayed implementation pathway, and the difference is summed over the entire period (2015–2060).

3. Conclusions

To comply with the Paris Climate Agreement and maintain the global temperature ‘well below +2.0 °C’, the rapid decarbonization of the energy sector with currently available technologies is necessary, and also possible. The normative scenarios developed here avoid an emissions overshoot by combining the transformation to a fully renewable energy supply with the utilization of the available efficiency potentials in all energy sectors to reduce the total demand. Significant electrification of the transport and heating sectors before 2030 is essential to meet the Paris goals in both scenarios presented here. Increased electrification will require sector coupling, demand-side management, and multiple forms of storage (heat and power), including synthetic fuels. Accelerating the implementation of renewable heat technologies is equally important, because half the global energy supply may still derive from thermal processes by 2050. The fundamental transition of the global energy sector shown in our pathways will only be possible with significant policy changes and energy market reforms. The COVID-19 pandemic is both an opportunity for and a threat to this transition. The International Renewable Energy Agency (IRENA), the International Energy Agency (IEA), and the International Monetary Fund (IMF), as well as various government and non-governmental organisations, are demanding stimulation packages for a sustainable economic recovery in order to create new employment in the renewable energy and energy efficiency industries. Despite the expectation of a rapid economic recovery and existing emergencies, new frameworks for fundamental changes in energy use and supply would be required, so that a quick return to business as usual would be avoided.

However, our scenario analysis demonstrates that maintaining the global temperature ‘well below +2.0 °C’ cannot be achieved by the decarbonization of the energy sector alone, but will also require significant changes in land use, including the rapid phase-out of

deforestation and significant reforestation. These measures are not alternative options to the decarbonization of the energy sector, but shall be implemented in parallel. If governments fail to act and mitigation is delayed, we face a serious risk of exceeding the carbon budget. Under the 1.5 °C Scenario, the additional emissions arising from delayed action (Figure 5) can be compensated if we rely more strongly on atmospheric CO₂ removal via biospheric sequestration—in land and forests.

Without additional delay, only one-third of the total estimated CO₂ removal potential will be required in the 2 °C-compatible pathway—leaving space to increase the amount of removal and still meet the 2 °C objective, albeit with the greater risk that a reliance on biospheric removal entails. However, our 1.5 °C pathway already requires all this biospheric sequestration potential—so a delay in mitigation action will put the 1.5 °C pathway out of reach. The idea of compensating emission overshoots in the long term by additional tree planting is unrealistic because the potential for terrestrial carbon sequestration and storage is limited by the amount of carbon previously lost from the biosphere through land conversion [38,47]. Our 1.5 °C pathway tends towards the upper end of this terrestrial carbon sink capacity. Therefore, significant extension of this already covered land sequestration potential is not possible without options that could be described as “geo-engineering”, such as establishing large tree plantations beyond ecosystem boundaries—a solution more vulnerable to the reversal of stored carbon [39]; or geological storage, such as via BECCS—an option likely to transgress planetary boundaries at the gigaton scale required for the 1.5 °C pathways [48]. Delayed mitigation action that is justified by sequestration, and which thus shifts the burden to the land sector, brings a higher risk of mitigation failure and temperature overshoot [49]. In our scenarios, the land-use sequestration pathways complement very ambitious energy-mitigation pathways. Sequestration of CO₂ is therefore regarded as necessary to compensate for past emissions and not for current or future emissions

4. Reflections on Ways of Implementation

Achieving a 2.0 °C or 1.5 °C target requires substantial and long-lasting policy changes in order to unlock the necessary investments in the energy sector. A refocused investment strategy towards emerging and green technologies could also support the recovery of the global economy after the pandemic. Solar photovoltaic and onshore wind energy, in particular, are not only cost competitive with conventionally generated energy, but are increasingly least cost options [9]. The volume of global investment in renewables decreased from USD 328 billion in 2017 to USD 289 billion in 2018 [50] and increased to USD 301.7 billion in 2019 [44], which is still 9% below the 2017 levels, even though total installed capacity increased in the same time [51].

The barriers to the deployment of renewable energies are diverse and country-specific. Therefore, the implementation targets vary significantly across the world regions.

The scenario studies show very clearly that the biggest challenge for North America, Europe and the Pacific region will be to rapidly reduce the high energy intensities, i.e., in particular to significantly reduce energy waste inherent in the industrialized lifestyle. Incentives to avoid rebound effects and to save energy in private consumption are not yet visible anywhere. Europe has above all variable renewable resources and must optimize their integration into the energy system through extensive flexibility measures [24,52,53]. However, Europe also has the promising option of sourcing energy imports from resource-rich regions in North Africa and the Middle East, which has long been under discussion [54–56]. In the OECD Pacific region, imports and exports of synthetic fuels (e.g., between Japan and Australia) could be a likely strategy to support 100% renewable energy systems [57]. In Latin America, an important strategy is to improve the sustainability of renewable resource use by redirecting traditional biomass to efficient and low-emission uses. In addition, it may be important to limit the expansion of large hydropower to minimize negative social and environmental impacts. Both narratives are reflected in our alternative goal-oriented paths.

Particularly in the Earth's sunbelt, the development of hydrogen and synthetic fuel technologies could not only cover domestic demand for chemical energy sources at moderate costs, but also open up future export markets [58,59]. In many countries, however, greater political stability would be a prerequisite for large investment in renewable energy and fuel production. The scenario development has clearly demonstrated that developments in China and India also have a major impact on global energy change. While China is already taking a leading position in several transformation processes, but the speed of its actions is not yet sufficient to achieve long-term goals [60].

The results of our scenarios show that the regional targets for the energy and land-use sectors can provide high-level mid- and long-term policy objectives and therefore investment security. In the energy sector, a combination of regional targets for electrification in all demand sectors (see Table 2) and targets for the maximum carbon intensity for each sector (see Table 3) provide a framework for the medium- and long-term measures required to convert the energy supply, including the energy infrastructure. Binding targets for land use will regulate the areas required for the future protection and restoration of carbon sinks and stocks (e.g., forests) and could also define the expansion of areas for renewable energy generation.

5. Similarities to Published Analysis, Research Limitations and Further Research Requirements

Our results in the energy sector are supported by results of other high renewable energy penetration scenarios [61,62]. However, the role of storage technologies, renewable fuels—such as hydrogen and synthetic fuels—and the extend of electrification of industrial process heat varies significantly. Furthermore, the presented 1.5 °C mitigation pathways do not rely on CCS and/or BECCS and used nature-based carbon sinks instead. The global scale of our energy pathways represents a research limitation as regional differences needed to be simplified. Future load curves are speculative as load management as well as utilization of storage technologies requires more research. The industry sector—with a focus on renewable energy supply options for high temperature process heat—requires more research as well. Decarbonisation pathways for specific industry sectors are required. Finally, the integration of non-energy GHG pathways, land-use change emission pathways and energy scenarios of high resolution need to be improved as current models—especially those used in the IPCC assessment reports are still simplistic.

6. Methodology

In our analysis, we considered the complete energy sector in detail, including electricity, heating and cooling, and transport. We also included a perspective on the non-energy use of fuels and the emission reductions arising from land-use changes, and provided a complete picture of all GHG emissions, extending the focus far beyond CO₂ and the energy sector. This was achieved by integrating a set of assessment models for both the energy and non-energy GHG sectors. The results of the various emission modelling tasks are embedded within the reduced-complexity model MAGICC7 (see e.g., [63]), which allowed the derivation of probabilistic temperature projections with which to assess the likelihood of maintaining the global temperature below 2.0 °C or 1.5 °C. The following section summarizes the applied models and their interactions (Figure 6).

6.1. Non-Energy GHG Emissions Scenarios

We complemented the CO₂ emission pathways from the energy system modeling with non-energy-related GHG emissions. To model the non-energy sector, we used different approaches, first to derive the land-use CO₂ emissions and then to derive the emissions of other GHGs and aerosols. In the first approach, we used a (probabilistic) scenario of land-use emissions based on four narrative land-use pathways, and in the second, we used a newly extended statistical regression method. The following two paragraphs describe, in more detail, the methods used in these approaches.

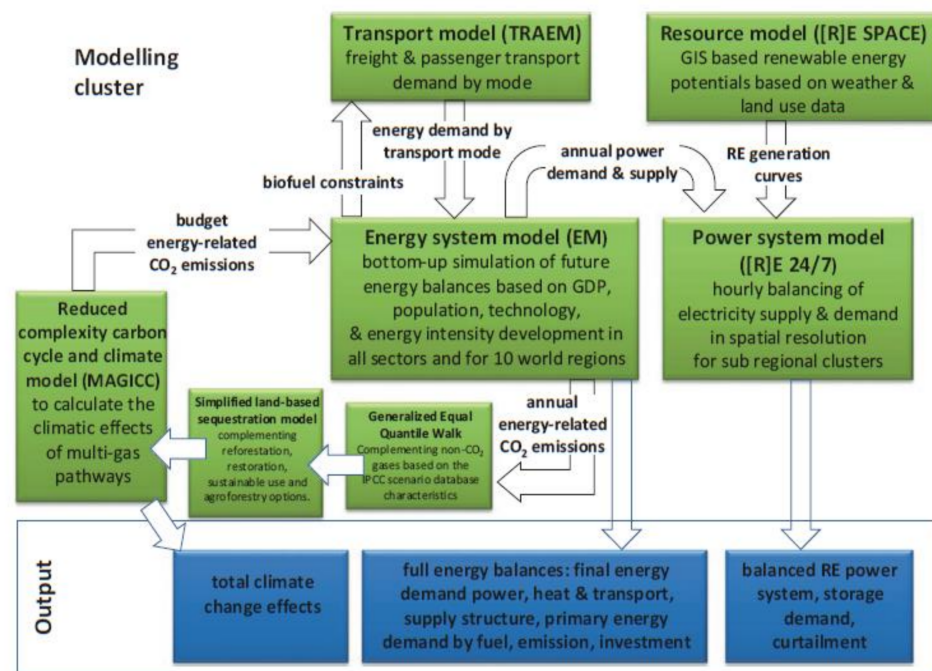


Figure 6. Interaction of the models used in this study.

6.1.1. Generalized Equal Quantile Walk (GQW)

A statistical analysis of 811 multi-gas emission pathways published by the Intergovernmental Panel on Climate Change (IPCC) [7,49] was carried out in order to complete the energy-related CO₂ emission paths with scenarios of other relevant greenhouse gases. The method is an extension of the Equal Quantile Walk method [64] which calculates the median value of greenhouse gases (excluding CO₂) as a function of CO₂ paths in 5-year steps. Further details on this methodology are published in [14].

6.1.2. Land-Based Sequestration Pathways

CO₂ sequestration can be achieved through improved land use such as “restoration of the forest ecosystem”, “reforestation”, “sustainable forest use” and “agroforestry”. Under the assumption that declassified carbon stocks can be restored through sustainable forest use, protected area management and improved land use with the aim of restoring carbon stocks, significant amounts of atmospheric CO₂ can be removed [38,65,66].

Four different sequestration pathways were defined based on literature research and available data from FAO statistics. Assuming that after several years of sustainable land management, a defined amount of carbon is bound annually and thus become carbon sinks. Ultimately, an equilibrium of atmospheric CO₂ is reached. When this equilibrium is reached depends on the type of ecosystem [67]. The phase of transition from a carbon sink to equilibrium is defined as the “phase-out” period.

A maximum of the mean carbon density was assumed based on bio-averaged values for the carbon density of undisturbed forest ecosystems per hectare [68], rather than on average global biome values [69]. The land use sequestration scenarios were calculated up to the year 2300, while the energy scenarios were only calculated until 2050 and the non-energy-related GHGs until 2100. The longer scenario period was necessary to apply the upper limit for the additional carbon density and to quantify the potential for CO₂ sequestration on land. Further details on the methodology are documented in [14].

6.2. Modelling the Energy Sector

To model the energy sector, we combined two complementary approaches: highly spatially and geographically resolved power system modelling and long-term pathway

development on an annual basis. The Energy System Model (EM) provides annual energy balances for the complete energy system. The model includes the energy demands for the industry, transport, residential, and others sectors, based on the external inputs of population, GDP, and energy intensity. The industry, residential, and other sectors are each represented by a set of heat, power, and co-generation technologies for all relevant fuel types. The transport sector is supplemented with a detailed transport model (TRAEM), including mobility demand and supply, based on transport technologies (e.g., vehicle types) and mobility services. The IEA World Energy Balances 2017 are the basis for calibrating the 2015 energy demand by region and sector in the model [70]. The conversion-and-power sector in the EM is complemented with a detailed power analysis. EM provides the power demand according to application type as an input parameter for the power system modelling. Based on this input, [R]E 24/7 calculates the necessary infrastructure for the power supply system. This suite of models was used to develop normative, target-oriented long-term scenarios. Starting from the base year and the identified desirable future in 2050 of net zero CO₂ emissions, narratives for suitable transformation pathways were developed. Climate targets in terms of the cumulative CO₂ emissions were set for both the 2.0 °C and a 1.5 °C scenario. To meet these, we constructed bottom-up scenarios covering a switch in the supply technologies. The scenarios are based on detailed input datasets that consider defined CO₂ mitigation and technology expansion targets and limits, potentials and costs for renewables and fossil energy sources, and specific technical parameters for electricity, heat, and fuel generation in the energy systems. We applied a technology transition to all the energy sectors using a gradual approach. We identified the largest remaining emitters based on an ex-post analysis of CO₂ emissions and the gap to reaching the overall CO₂ budget. We then applied additional measures for an accelerated transition towards renewable energy technology. This iterative process was repeated until the carbon budget limitation was achieved.

6.2.1. Transport Model (TRAEM)

The TRANsport Energy Model (TRAEM) calculates energy demand pathways, broken down into 10 world regions. Based on a passenger–km (pkm) and tonne–km (tkm) activity-based approach, these energy demands were integrated into a global model. The model calculates the final energy demand as the product of specific transport demand of each transport mode with the powertrain-specific energy demand. The model determines the transport energy demand for electricity and various fuels per year in 5-year intervals from 2015 to 2050, with no system or ownership cost-optimization. Total energy demand in the REF Scenario (5.0 °C) follows the IEA World Energy Outlook 2017 Current Policies Scenario [15] up to 2040. Based on the 2035–2040 change rates energy demand was extrapolated linearly to 2050 on regional level. The was alternative scenarios were adjusted from 2020 to 2050 according to the respective carbon budgets. We attributed biofuels a GHG emission factor of zero because we assume that CO₂ is fixed in the upstream process at the same level as the downstream CO₂ emission. The same applies for CO₂ emissions from synthetic fuel use. The model distinguishes different road passenger transport modes (light-duty vehicles are separated into small, medium, and large cars, 2- and 3-wheelers, and buses), rail passenger transport (urban, regional, and high-speed trains), and aviation (domestic and international passenger flights). Road freight (light-, medium-, and heavy-duty trucks), rail freight, and navigation freight transport were also considered.

Energy intensities per activity varies between the regions, based on the occupancy/load rates of the passenger transport modes or freight vehicles. Total energy demand is then the sum of all demand in all transport modes. The transport data were derived from historical and current transport activity data from statistics, complemented by region specific literature (for example, data on vehicle stock or occupancy rates in selected world regions). The German Aerospace Center (DLR) vehicle databases served as source for energy intensity per transport. More information on this database and more details and the key assumptions can be found in [71].

6.2.2. Energy System Model (EM)

The scenarios are developed within a mathematical accounting system, specifically developed for the energy sector. It models development ways for energy demand and supply, considering development pathways of potentials, specific fuel consumption, technology and fuel costs, emissions, and limitations by physical flows between a set of technology processes. The data availability and the objectives of the analysis significantly influence the model architecture and approach.

The scenarios are implemented in Mesap/PlaNet, an energy simulation platform, which hosts the global energy system model developed by the DLR [72,73]. The accounting framework calculates detailed and consistent energy system balances, starting from demand and working all the way back to primary energy supply. It consists of two independent modules:

- the flow calculation module with a physical balance of energy supply and demand on annual basis;
- the cost calculation module, for corresponding investment, generation and supply costs.

The model integrates and combines a whole range of different technical options for the transformation of energy systems. The ex-post evaluation of power cost calculation is implemented via the Mesap platform's standard tool and applied to all scenarios. The Model features a database for managing the input parameters and the output for the different scenarios after simulation. The graphical interface serves for structuring the modelled system and defining the quantitative interdependences between individual elements at different structural depths. Details of the structure and relevant model equations are given in the literature [21,74]. The energy flows of the energy system are balanced in the model on an annual basis. These flows connect technologies in each sector to process chains and includes all relevant energy carriers, using linear equations. The model then balances demand and supply by sequentially solving this equation system. The scenario period is disaggregated to 5-year steps until 2050. Further details about the methodology of the Energy System Model (EM) are published in [14]. The main outputs of the model are:

- primary and final energy demands, disaggregated by fuel, technology, and energy sector, according to the classification by the International Energy Agency (IEA);
- required energy required, applied technology and the financial investment for electricity, heating, and mobility (transport);
- total cost of energy for the power system;
- energy-related CO₂ emissions over the scenario period.

6.3. Modelling the Power Sector

The power system analysis [R]E 24/7 is a mathematical accounting system that assess the requirements for electricity storage (the calculation of inter-regional exchange capacity requirements in MW is also possible, but beyond the scope of this article). It simulates the electricity system on an hourly basis and at geographic resolution. The methodology of the [R]E 24/7 model has been developed by UTS/ISF [75–78]. It specifically implements the hourly distribution (load curves and storage) and the geographic distribution of power demand and supply.

Hourly load curves for the residential, industry, and transport sectors were synthetically produced on the basis of the annual electricity demands for 2020, 2030, 2040, and 2050 (EM results), technology- and sector-specific energy intensity factors, regional GDP [79], and population data. Load curves for households were determined using nine different household categories, with various degrees of electrification and equipment. To calculate the load curves for business and industry, eight statistical industrial-sector categories were used: agriculture (1), manufacturing (2), mining (3), iron and steel production (4), cement industry (5), construction industry (6), chemical industry (7), and service and trade (8). Each sector had a defined energy intensity, expressed in energy per dollar GDP (MJ/USD_{GDP}),

which was converted to electrical units (kW/USD_{GDP}) based on an estimated fuel efficiency factor, the electricity share, and operational hours per year. The load curve for the transport sector was calculated from the energy intensities for all electricity-consuming transport modes and hydrogen and synthetic fuel production, divided by the average annual utilization according to the technology (in h/yr). All three sectorial load curves were standardized: the load curves for the household and transport sectors in kilowatts per person (kW/capita) and the industry load curves in kilowatts per dollar GDP (kW/USD GDP). These standard curves were multiplied by the GDP data for each regional population. The standardized sectorial load curves for households and transport were multiplied by the population numbers derived with GIS mapping of each cluster. The standardized load curves for each of the eight industry sectors were multiplied by the corresponding shares of the total GDP values accorded these sectors by region. Because some data for each cluster were unavailable, the eight regional industry load curves were distributed per capita. In the last step, all sectorial load curves (households, transport, and industry) were summed. The spatial distribution of the projected GDP by industry sector remained unchanged in the 72 sub-regions over the years modelled (2020–2050).

The calculated load curves were compared with a cascade of power-generation technologies. The dispatch orders of the power-plant technologies can be changed. If demand and generation are congruent, no subsequent power-plant technologies are required, and the production for these hours will be zero. For variable solar and wind power generation, meteorological data with hourly resolution are required for each cluster (see [80,81]). Further details about the methodology are documented in [14].

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References

- IRENA. *Scenarios for the Energy Transition: Global Experiences and Best Practices*; International Renewable Energy Agency: Abu Dhabi, United Arab Emirates, 2020; ISBN 978-92-9260-267-3.
- United Nations Framework Convention on Climate Change (UNFCCC). The Paris Agreement. Available online: http://unfccc.int/paris_agreement/items/9485.php (accessed on 12 March 2018).
- Rogelj, J.; Popp, A.; Calvin, K.V.; Luderer, G.; Emmerling, J.; Germain, D.; Fujimori, S.; Strefler, J.; Hasegawa, T.; Marangoni, G.; et al. Scenarios towards limiting global mean temperature increase below 1.5 °C. *Nat. Clim. Chang.* **2018**, *8*, 325–332. [[CrossRef](#)]
- Kriegler, E.; Riahi, K.; Bauer, N.; Schwanitz, V.J.; Petermann, N.; Bosetti, V.; Marcucci, A.; Otto, S.; Paroussos, L.; Rao, S.; et al. Making or breaking climate targets: The AMPERE study on staged accession scenarios for climate policy. *Technol. Forecast. Soc. Chang.* **2015**, *90*, 24–44. [[CrossRef](#)]
- International Energy Agency (IEA). *World Energy Outlook 2018*; OECD Publishing: Paris, France, 2018. [[CrossRef](#)]
- Rogelj, J.; Elzen, M.D.; Höhne, N.; Fransen, T.; Fekete, H.; Winkler, H.; Schaeffer, R.; Sha, F.; Riahi, K.; Meinshausen, M. Paris Agreement climate proposals need a boost to keep warming well below 2°C. *Nature* **2016**, *534*, 631–639. [[CrossRef](#)] [[PubMed](#)]
- Intergovernmental Panel on Climate Change (IPCC). *AR5 Synthesis Report: Climate Change 2014*; IPCC: Geneva, Switzerland, 2014. Available online: <https://www.ipcc.ch/report/ar5/syr/> (accessed on 24 March 2021).

8. Intergovernmental Panel on Climate Change (IPCC). *Global Warming of 1.5 °C*; IPCC: Geneva, Switzerland, 2014. Available online: https://www.ipcc.ch/site/assets/uploads/sites/2/2019/06/SR15_Full_Report_High_Res.pdf (accessed on 24 March 2021).
9. Lazard. Lazard's Levelized Costs of Energy Analysis—Version 13.0. Available online: <https://www.lazard.com/media/451086/lazards-levelized-cost-of-energy-version-130-vf.pdf> (accessed on 24 November 2019).
10. Fridahl, M.; Lehtveerac, M. Bioenergy with carbon capture and storage (BECCS): Global potential, investment preferences, and deployment barriers. *Energy Res. Soc. Sci.* **2018**, *42*, 155–165. [[CrossRef](#)]
11. Ramana, M.V. Technical and social problems of nuclear waste. *Wiley Interdiscip. Rev. Energy Environ.* **2018**, *7*, e298. [[CrossRef](#)]
12. Shaffer, G. Long-term effectiveness and consequences of carbon dioxide sequestration. *Nat. Geosci.* **2010**, *3*, 464–467. [[CrossRef](#)]
13. Intergovernmental Panel on Climate Change (IPCC). *Global Warming of 1.5 °C*; (See above), SR1.5 p.132, Table 2.6.; IPCC: Geneva, Switzerland, 2019. Available online: https://www.ipcc.ch/site/assets/uploads/sites/2/2019/06/SR15_Full_Report_High_Res.pdf (accessed on 24 March 2021).
14. Teske, S. (Ed.) *Achieving the Paris Climate Agreement Goals—Global and Regional 100% Renewable Energy Scenarios with Non-Energy GHG Pathways for +1.5 °C and +2 °C*; Springer eBook: New York, NY, USA, 2019. [[CrossRef](#)]
15. International Energy Agency (IEA). *World Energy Outlook 2017*; OECD Publishing: Paris, France, 2017. [[CrossRef](#)]
16. Intergovernmental Panel on Climate Change (IPCC). *AR5 Climate Change 2014: Mitigation of Climate Change*; IPCC: Geneva, Switzerland, 2014. Available online: <https://www.ipcc.ch/report/ar5/wg3/> (accessed on 24 March 2021).
17. United Nations, Department of Economic and Social Affairs, Population Division. *World Population Prospects: The 2017 Revision*; United Nations: New York, NY, USA, 2017. Available online: <https://population.un.org/wpp/> (accessed on 30 April 2018).
18. Graus, W.J.; Blomen, E.; Worrell, E. Global energy efficiency improvement in the long term: A demand- and supply-side perspective. *Energy Effic.* **2011**, *4*, 435–463. [[CrossRef](#)]
19. Kermeli, K.; Graus, W.J.; Worrell, E. Energy efficiency improvement potentials and a low energy demand scenario for the global industrial sector. *Energy Effic.* **2014**, *7*, 987–1011. [[CrossRef](#)]
20. Grubler, A.; Wilson, C.; Bento, N.; Boza-Kiss, B.; Krey, V.; Mccollum, D.L.; Rao, N.D.; Riahi, K.; Rogelj, J.; De Stercke, S.; et al. A low energy demand scenario for meeting the 1.5 °C target and sustainable development goals without negative emission technologies. *Nat. Energy* **2018**, *3*, 515–527. [[CrossRef](#)]
21. Pregger, T.; Simon, S.; Naegler, T.; Teske, S. Main Assumptions for Energy Pathways. In *Achieving the Paris Climate Agreement Goals: Global and Regional 100% Renewable Energy Scenarios with Non-Energy GHG Pathways for +1.5 °C and +2 °C*; Teske, S., Ed.; Springer International Publishing: New York, NY, USA, 2019; pp. 93–130.
22. Lovins, A.B. How big is the energy efficiency resource? *Environ. Res. Lett.* **2018**, *13*, 09041. [[CrossRef](#)]
23. Teske, S.; Pregger, T.; Naegler, T.; Simon, S.; Pagenkopf, J.; van den Adel, B.; Deniz, Ö. Energy Scenario Results. In *Achieving the Paris Climate Agreement Goals: Global and Regional 100% Renewable Energy Scenarios with Non-Energy GHG Pathways for +1.5 °C and +2 °C*; Teske, S., Ed.; Springer International Publishing: New York, NY, USA, 2019; pp. 175–401.
24. Gils, H.C.; Simon, S.; Soria, R. 100% renewable energy supply for Brazil—The role of sector coupling and regional development. *Energies* **2017**, *10*, 1859. [[CrossRef](#)]
25. Xiao, M.; Simon, S.; Pregger, T. Scenario analysis of energy system transition—A case study of two coastal metropolitan regions, eastern China. *Energy Strategy Rev.* **2019**, *26*, 100423. [[CrossRef](#)]
26. Xiao, M.; Wetzel, M.; Pregger, T.; Simon, S.; Scholz, Y. Modeling the supply of renewable electricity to metropolitan regions in China. *Energies* **2020**, *13*, 3042. [[CrossRef](#)]
27. Falchetti, G.; Pachauri, S.; Byers, E.; Danylo, O.; Parkinson, S.C. Satellite observations reveal inequalities in the progress and effectiveness of recent electrification in sub-Saharan Africa. *One Earth* **2020**, *2*, 364–379. [[CrossRef](#)]
28. Müller, R.; Pfeifroth, U.; Träger-Chatterjee, C.; Trentmann, J.; Cremer, R. Digging the METEOSAT Treasure—3 decades of solar surface radiation. *Remote Sens.* **2015**, *7*, 8067–8101. [[CrossRef](#)]
29. The Renewables.ninja. RE-N DB 2018, online database for hourly time series for solar and wind data for a specific geographical position. Available online: <https://www.renewables.ninja/> (accessed on 7 July 2018).
30. Sask Power. Boundary Dam Carbon Capture Project. Available online: <https://www.saskpower.com/Our-Power-Future/Infrastructure-Projects/Carbon-Capture-and-Storage/Boundary-Dam-Carbon-Capture-Project> (accessed on 20 March 2020).
31. Armpriester, A.W.A. *Parish Post Combustion CO2 Capture and Sequestration Project*; Final Public Design Report for the U.S. Department of Energy, Office of Scientific and Technical Information, 17 February 2017. Available online: <https://www.osti.gov/biblio/1344080> (accessed on 20 March 2020).
32. Global CCS Institute. *Global Status of CCS 2019—Targeting Climate Change*. (p. 24, Figure 8). Available online: https://www.globalccsinstitute.com/wp-content/uploads/2019/12/GCC_GLOBAL_STATUS_REPORT_2019.pdf (accessed on 20 March 2020).
33. Fuss, S.; Lamb, W.F.; Callaghan, M.W.; Hilaire, J.; Creutzig, F.; Amann, T.; Beringer, T.; Garcia, W.D.O.; Hartmann, J.; Khanna, T.; et al. Negative emissions—Part 2: Costs, potentials and side effects. *Environ. Res. Lett.* **2018**, *13*, 063002. [[CrossRef](#)]
34. Turner, P.A.; Mach, K.J.; Lobell, D.B.; Benson, S.M.; Baik, E.; Sanchez, D.L.; Field, C.B. The global overlap of bioenergy and carbon sequestration potential. *Clim. Chang.* **2018**, *148*, 1–10. [[CrossRef](#)]
35. Griscom, B.W.; Adams, J.; Ellis, P.W.; Houghton, R.A.; Lomax, G.; Miteva, D.A.; Schlesinger, W.H.; Shoch, D.; Siikamäki, J.V.; Smith, P.; et al. Natural climate solutions. *Proc. Natl. Acad. Sci. USA* **2017**, *114*, 11645–11650. [[CrossRef](#)]
36. Roe, S.; Streck, C.; Obersteiner, M.; Frank, S.; Griscom, B.; Drouet, L.; Fricko, O.; Gusti, M.; Harris, N.; Hasegawa, T.; et al. Contribution of the land sector to a 1.5 °C world. *Nat. Clim. Chang.* **2019**, *9*, 817–828. [[CrossRef](#)]

37. Teske, S.; Pregger, T.; Simon, S.; Naegler, T.; Pagenkopf, J.; van den Adel, B.; Meinshausen, M.; Dooley, K.; Briggs, C.; Dominish, E.; et al. Methodology. In *Achieving the Paris Climate Agreement Goals: Global and Regional 100% Renewable Energy Scenarios with Non-Energy GHG Pathways for +1.5 °C and +2 °C*; Teske, S., Ed.; Springer International Publishing: New York, NY, USA, 2019; pp. 25–78.
38. Mackey, B.; Prentice, I.C.; Steffen, W.; House, J.I.; Lindenmayer, D.; Keith, H.; Berry, S. Untangling the confusion around land carbon science and climate change mitigation policy. *Nat. Clim. Chang.* **2013**, *3*, 552–557. [[CrossRef](#)]
39. Seddon, N.; Turner, B.; Berry, P.; Chausson, A.; Girardin, C. Grounding nature-based climate solutions in sound biodiversity science. *Nat. Clim. Chang.* **2019**, *9*, 84–87. [[CrossRef](#)]
40. Lewis, S.L.; Wheeler, C.E.; Mitchard, E.T.A.; Koch, A. Regenerate natural forests to store carbon. *Nature* **2019**, *568*, 25–28. [[CrossRef](#)]
41. Meinshausen, M.; Dooley, K. Mitigation Scenarios for Non-energy GHG. In *Achieving the Paris Climate Agreement Goals: Global and Regional 100% Renewable Energy Scenarios with Non-Energy GHG Pathways for +1.5 °C and +2 °C*; Teske, S., Ed.; Springer International Publishing: New York, NY, USA, 2019; pp. 79–91.
42. Global Energy Assessment 2012. *Annex II, Technical Guidelines: Common Terms, Definitions and Units Used in GEA*; Cambridge University Press: Cambridge, UK; New York, NY, USA; International Institute for Applied Systems Analysis: Laxenburg, Austria; p. 1816. Available online: https://www.iiasa.ac.at/web/home/research/Flagship-Projects/Global-Energy-Assessment/GEA_Annex_II.pdf (accessed on 24 March 2021).
43. International Energy Agency (IEA). Sustainable Recovery—World Energy Outlook Special Report. In *Collaboration with the International Monetary Fund*; OECD Publishing: Paris, France, 2020. Available online: <https://www.iea.org/reports/sustainable-recovery> (accessed on 24 March 2021).
44. Renewable Energy Policy Network for the 21st Century (REN21). *Renewables 2020 Global Status Report*; REN21 Secretariat: Paris, France, 2020. Available online: <https://www.ren21.net/gsr-2020/> (accessed on 24 March 2021).
45. Wells, C.R.; Sah, P.; Moghadas, S.M.; Pandey, A.; Shoukat, A.; Wang, Y.; Wang, Z.; Meyers, L.A.; Singer, B.H.; Galvani, A.P. Impact of international travel and border control measures on the global spread of the novel 2019 coronavirus outbreak. *PNAS* **2020**, *117*, 7504–7509. [[CrossRef](#)]
46. International Energy Agency (IEA). Global CO₂ Emissions in 2019. Available online: <https://www.iea.org/articles/global-co2-emissions-in-2019> (accessed on 11 February 2020).
47. Arneeth, A.; Sitch, S.; Pongratz, J.; Stocker, B.D.; Ciais, P.; Poulter, B.; Bayer, A.D.; Bondeau, A.; Calle, B.P.L.; Chini, L.P.; et al. Historical carbon dioxide emissions caused by land-use changes are possibly larger than assumed. *Nat. Geosci.* **2017**, *10*, 79–84. [[CrossRef](#)]
48. Heck, V.; Gerten, D.; Lucht, W.; Popp, A. Biomass-based negative emissions difficult to reconcile with planetary boundaries. *Nat. Clim. Chang.* **2018**, *8*, 151–155. [[CrossRef](#)]
49. Intergovernmental Panel on Climate Change (IPCC). *Climate Change and Land*; IPCC: Geneva, Switzerland, 2019. Available online: <https://www.ipcc.ch/srccl/> (accessed on 24 March 2021).
50. Renewable Energy Policy Network for the 21st Century (REN21). *Renewables 2019 Global Status Report*; REN21 Secretariat: Paris, France, 2019. Available online: <https://www.ren21.net/gsr-2019/> (accessed on 30 March 2020).
51. International Renewable Energy Agency. Renewable Energy Statistics 2020. Available online: <https://www.irena.org/Statistics/> (accessed on 24 March 2021).
52. Brown, T.; Schlachtberger, D.; Kies, A.; Schramm, S.; Greiner, M. Synergies of sector coupling and transmission reinforcement in a cost-optimised, highly renewable European energy system. *Energy* **2018**, *160*, 720–739. [[CrossRef](#)]
53. Borowski, P.F. Zonal and Nodal Models of Energy Market in European Union. *Energies* **2020**, *13*, 4182. [[CrossRef](#)]
54. Trieb, F.; Schillings, C.; Pregger, T.; O’Sullivan, M. Solar electricity imports from the Middle East and North Africa to Europe. *Energy Policy* **2012**, *42*, 341–353. [[CrossRef](#)]
55. Pregger, T.; Lavagno, E.; Labriet, M.; Seljom, P.; Biberacher, M.; Blesl, M.; Trieb, F.; O’Sullivan, M.; Gerboni, R.; Schranz, L.; et al. Resources, capacities and corridors for energy imports to Europe. *Int. J. Energy Sector Manag.* **2011**, *5*, 125–156. [[CrossRef](#)]
56. Dii Desert Energy. A North Africa—Europe Hydrogen Manifesto. 2019. Available online: <https://dii-desertenergy.org/wp-content/uploads/2019/12/Dii-hydrogen-study-November-2019.pdf> (accessed on 1 October 2020).
57. PV Magazine. Australia and Japan Agree to Hydrogen Future. 24 January 2020 Blake Matich. Available online: <https://www.pv-magazine-australia.com/2020/01/24/australia-and-japan-agree-to-hydrogen-future/> (accessed on 10 October 2020).
58. European Commission. A Hydrogen Strategy for a Climate-neutral Europe. Brussels, 8.7.2020 COM(2020) 301 final. Available online: https://ec.europa.eu/energy/sites/ener/files/hydrogen_strategy.pdf (accessed on 12 October 2020).
59. Timmerberg, S.; Kaltschmitt, M. Hydrogen from renewables: Supply from North Africa to Central Europe as blend in existing pipelines—Potentials and costs. *Appl. Energy* **2019**, *237*, 795–809. [[CrossRef](#)]
60. Xiao, M.; Simon, S.; Pregger, T. Energy System Transitions in the Eastern Coastal Metropolitan Regions of China—The Role of Regional Policy Plans. *Energies* **2019**, *12*, 389. [[CrossRef](#)]
61. Jacobson, M.Z.; Delucchi, M.A.; Bauer, Z.A.; Goodman, S.C.; Chapman, W.E.; Cameron, M.A.; Bozonnat, C.; Chobadi, L.; Clonts, H.A.; Enevoldsen, P.; et al. 100% Clean and Renewable Wind, Water, and Sunlight All-Sector Energy Roadmaps for 139 Countries of the World. *Joule* **2017**, *1*, 108–121. [[CrossRef](#)]

62. Breyer, C.; Bogdanov, D.; Aghahosseini, A.; Gulagi, A.; Child, M.; Oyewo, A.S.; Farfan, J.; Sadovskaia, K.; Vainikka, P. Solar photovoltaics demand for the global energy transition in the power sector. *Prog. Photovolt.* **2018**, *26*, 505–523. [CrossRef]
63. Meinshausen, M.; Raper, S.C.B.; Wigley, T.M.L. Emulating coupled atmosphere-ocean and carbon cycle models with a simpler model, MAGICC6—Part 1: Model description and calibration. *Atmos. Chem. Phys.* **2011**, *11*, 1417–1456. [CrossRef]
64. Meinshausen, M.; Hare, B.; Wigley, T.M.L.; van Vuuren, D.; den Elzen, M.G.J.; Swart, R. Multi-gas emission pathways to meet climate targets. *Clim. Chang.* **2006**, *75*, 151–194. [CrossRef]
65. DeCicco, J.M.; Schlesinger, W.H. Reconsidering bioenergy given the urgency of climate protection. *Proc. Natl Acad. Sci. USA* **2018**, *115*, 9642–9645. [CrossRef] [PubMed]
66. Luyssaert, S.; Schulze, E.-D.; Börner, A.; Knohl, A.; Hessenmöller, D.; Law, B.E.; Ciais, P.; Grace, J. Old-growth forests as global carbon sinks. *Nature* **2008**, *455*, 213–215. [CrossRef]
67. Houghton, R.A.; Nassikas, A.A. Negative emissions from stopping deforestation and forest degradation, globally. *Glob. Chang. Biol.* **2018**, *24*, 350–359. [CrossRef]
68. Keith, H.; Mackey, B.G.; Lindenmayer, D.B. Re-evaluation of forest biomass carbon stocks and lessons from the world’s most carbon-dense forests. *Proc. Natl Acad. Sci. USA* **2009**, *106*, 11635–11640. [CrossRef]
69. Liu, Y.Y.; Van Dijk, A.I.J.M.; De Jeu, R.A.M.; Canadell, J.G.; McCabe, M.F.; Evans, J.P.; Wang, G. Recent reversal in loss of global terrestrial biomass. *Nat. Clim. Chang.* **2015**, *5*, 470–474. [CrossRef]
70. International Energy Agency (IEA). *World Energy Balances 2017*; OECD Publishing: Paris, France, 2017. [CrossRef]
71. Pagenkopf, J.; van den Adel, B.; Deniz, Ö.; Schmid, S. Transport Transition Concepts. In *Achieving the Paris Climate Agreement Goals: Global and Regional 100% Renewable Energy Scenarios with Non-Energy GHG Pathways for +1.5 °C and +2 °C*; Teske, S., Ed.; Springer International Publishing: New York, NY, USA, 2019; pp. 131–159.
72. Schlenzig, C. Energy planning and environmental management with the information and decision support system MESAP. *Int. J. Glob. Energy Issues* **1998**, *12*, 81–91. [CrossRef]
73. SevenZone. *Mesap/PlaNet Software Framework*; SevenZone Modelling, Mesap4, Release 4.14.1.9; SevenZone Informationssysteme GmbH: Karlsruhe, Germany, 2012.
74. Simon, S.; Naegler, T.; Gils, H.C. Transformation towards a renewable energy system in Brazil and Mexico—Technological and structural options for Latin America. *Energies* **2018**, *11*, 907. [CrossRef]
75. Dunstan, C.; Fattal, A.; James, G.; Teske, S. *Towards 100% renewable energy for Kangaroo Island*; UTS-ISF: Sydney, Australia, 2016; Prepared by the Institute for Sustainable Futures, University of Technology Sydney (with assistance from AECOM); Final report prepared for ARENA, Renewables SA, and Kangaroo Island Council.
76. Teske, S. Bridging the Gap between Energy and Grid Models, Developing an Integrated Infrastructural Planning Model for 100% Renewable Energy Systems in order to Optimize the Interaction of Flexible Power Generation, Smart Grids and Storage Technologies. Ph.D. Thesis, University of Flensburg, Frensburg, Germany, 2015.
77. James, G.; Rutovitz, J.; Teske, S. *Storage Requirements for Reliable Electricity in Australia*; University of Technology Sydney, UTS-ISF: Sydney, Australia, 2017; Report prepared by the Institute for Sustainable Futures for the Australian Council of Learned Academies.
78. Teske, S.; Morris, T.; Nagrath, K. *100% Renewable Energy for Tanzania—Access to Renewable Energy for all Within one Generation*; University of Technology Sydney, UTS-ISF: Sydney, Australia, 2017; Report prepared by ISF for Bread for the World.
79. Central Intelligence Agency Library. World Factbook, Online Database. Available online: <https://www.cia.gov/library/publications/the-world-factbook/fields/2195.html> (accessed on 7 July 2018).
80. Pfenninger, S.; Staffell, I. Long-term patterns of European PV output using 30 years of validated hourly reanalysis and satellite data. *Energy* **2016**, *114*, 1251–1265. [CrossRef]
81. Staffell, I.; Pfenninger, S. Using bias-corrected reanalysis to simulate current and future wind power output. *Energy* **2016**, *114*, 1224–1239. [CrossRef]