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Title

Impact of declining renewable energy costs on electrification in low emission scenarios

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Abstract

Cost degression in photovoltaics, wind power and battery storage has been faster than previously anticipated. In the future, climate policy to limit global warming to 1.5-2°C will make carbon-based fuels increasingly scarce and expensive. Here we show that further progress in solar and wind power technology along with carbon pricing to reach the Paris Climate targets could make electricity cheaper than carbon-based fuels. In combination with demand-side innovation, for instance in e-mobility and heat pumps, this is likely to induce a fundamental transformation of energy systems towards a dominance of electricity-based end uses. In a 1.5°C-scenario with limited availability of bioenergy and carbon dioxide removal, electricity could account for 66% of final energy by mid-century, three times the current levels and substantially higher than in previous climate policy scenarios assessed by the IPCC. The lower production of bioenergy in our high electrification scenarios markedly reduces energy-related land and water requirements.

Main text

Energy transformation pathways limiting warming in line with the targets of the Paris Agreement exhibit a fundamental difference between the decarbonization of electric and non-electric energy[1–4]. Electric energy can be produced from renewable resources, in particular wind and solar power, at relatively low cost. By contrast, scenarios from Integrated Assessment Models (IAMs) demonstrate that non-electric fuels for the transportation, industry and buildings sectors – currently largely supplied from fossil fuels – are much more difficult to decarbonize[5,6]. There are a number of strategies to abate emissions from non-electric fuels, such as reducing final energy demand, reducing their atmospheric carbon emissions intensity (e.g. via biomass, carbon capture and storage (CCS)), or compensation via carbon dioxide removal (CDR). Since in particular bioenergy and CCS face greater resource and sustainability limitations than zero-carbon power[7–9], electrification of end uses becomes increasingly important.

There is a long-term trend towards higher quality, grid-based energy carriers[10]. Electricity reached 8% of global final energy in 1970, and accounted for 19% in 2015. The dominance of non-electric energy is mostly due to the higher provisioning cost of electricity vis-a-vis fuels. This is a direct consequence of the conversion losses when generating electricity from combustible fuels in thermal power plants, but also the high energy density and storability of fuels.

New renewable energy technologies, in particular solar photovoltaics (PV)[11], but also wind energy[12], have achieved rapid technological progress over the recent past, resulting in substantial cost decreases, competitiveness, system friendliness and a reduced environmental footprint. Renewable electricity is competitive with new conventional power generation in most world regions[12]. Battery technology is also evolving rapidly[13,14], enabling a large-scale transition towards battery-electric mobility[15,16], as well as storage facilitating the grid integration of variable renewable electricity. Similarly rapid innovation is observed to result in rapid cost decreases in numerous other electricity-based end-use technologies[17].

The goal of this study is to analyze the role and potential of electrification for global and long-term deep decarbonization strategies using REMIND-MAgPIE, an IAM of the coupled energy-land system representing technological change in both energy supply and end uses. The study presents a comprehensive picture of the dynamics, techno-economic requirements and full-systems implications of deep electrification. To the extent that solar and wind power become increasingly cheap and the reliance on bioenergy, CCS and CDR is questioned, renewables-based electrification becomes increasingly relevant. The study thus addresses criticism that the majority of IAM scenarios on the one hand over-emphasize bioenergy, CCS and CDR[18–20], and on the other hand underappreciate the pace of technological progress in solar energy[21] and energy end-use technologies[17,22]. Electricity-based end uses mostly also make more efficient use of energy than combustion processes, thus reducing overall energy demand without requiring a reduction in energy services. The scenarios presented here are closely related to the discourse on the feasibility of 100% renewables scenarios in the energy systems modeling (ESM) literature[20–22]. Methodologically, ESM scenarios are derived from models focusing on the energy supply system. Typically, these models feature high intra-annual temporal resolution, but lack a representation of the broader macroeconomic context that drives energy end use and determines economic efficiency in reaching climate goals. The REMIND-MAgPIE model, by contrast, represents the full systems context including competition with conventional energy supply technologies as well as the transformation of energy end uses. In the high-renewables scenarios of the ESM literature, the phase-out of fossil energy supply and electrification of demand are mostly prescribed. Here, by contrast, they are an emergent property of the energy-economic system under the given set of assumptions on the climate stabilization target, technology assumptions and constraints, as well as policy frameworks.

Deep decarbonization scenarios

The scenarios explored in this study are listed in Table 1. REMIND 2.1.3[23] was augmented with detailed representations of energy end uses and energy services in the buildings[24] and transportation sectors[25] that also account for a variety of electrification options (see Methods). In industry, the model differentiates the steel, chemicals, cement and other manufacturing subsectors in terms of their demands for process heat and mechanical work, as well as substitution of electricity and hydrogen for carbon-based fuel inputs. The climate policy scenarios considered here limit cumulative CO_2 emissions from 2020 onwards to 500 $GtCO_2$ (limiting warming to below 1.5°C by 2100 with ~0.1°C overshoot around mid-century (*1.5C)*) or 900 $GtCO_2$ (limiting warming to well below 2°C *(WB2C)*), consistent with CO_2 budget estimates from Ref.[26,27], and in line with the long-term objective of the Paris Agreement. The coupling of REMIND to the MAgPIE model[28] allows for the exploration of implications of alternative energy transformation pathways for land systems.

In the two core scenarios of this study, 1.5C-Elec and WB2C-Elec, global bioenergy supply is limited to 100 EJ/yr, and geological storage of captured carbon is limited to below 4.0 $GtCO_2$/yr globally. The model further assumes a continuation of technological learning-induced reductions of the capital costs of solar PV, wind power and battery storage in line with past experience rates and expectations for future cost degressions[14,29,30]. In the transport sector, we assume regulation and support policies for the market introduction of electric vehicles. These policies are assumed to be in place until 2035, a critical time frame to accelerate technological learning and promote early adoption by consumers (see Methods for details). For comparison, we also include two climate policy scenarios with more conventional technology orientation (1.5C-Conv, WB2C-Conv), as well as a weak climate policy scenario (Reference) assuming a mere continuation of currently implemented policies[31].

We further compare our results to scenarios from the prior integrated assessment modeling literature as compiled in the IPCC SR15 database[32]. We refer to the superset of the categories “below 1.5C”, “1.5C low overshoot” and “1.5C high overshoot” in the database as *SR15-1.5C*, and to “lower 2°C” scenarios as *SR15-WB2C* sets.

Table 1|Overview of the scenarios considered in this study.

Scenario	Description
1.5C-Elec	Global climate policy efforts limiting warming to below 1.5°C (carbon budget from 2020 limited to 500 $GtCO_2$ not-to-exceed). *Technology constraints:* ● Global biomass availability limited to 100 EJ/yr (compared to 55 EJ/yr currently), phase out of 1st gen. bioenergy until 2070. ● Annual geological CO_2 sequestration limited to 0.1% of technical geological storage potential in each region, limiting global injection to below 4 $GtCO_2$. *Variable renewable electricity generation and integration:* ● Continued fast cost decreases in wind, solar, battery technology ● Learning rate of solar PV of 25% per doubling of cumulative capacity, floor costs of 100 US$2015/kW resulting in utility-scale system costs of ~190 US$2015/kW in 2050, consistent with Vartiainen et al.[26]. ● Integration of variable renewable electricity (VRE) via battery storage, flexible hydrogen generation and flexibilization of demand *Demand side electrification:* ● Market introduction via subsidies for battery electric vehicles (BEVs) 2021-2035, accelerated build-up of charging infrastructure to promote consumer acceptance ● Adoption of competitive demand-side electrification technologies in buildings and industry
WB2C-Elec	Like 1.5C-Elec, but cumulative 2020-2100 CO_2 emissions limited to 900 $GtCO_2$, limiting warming to well below 2°C.
1.5C-Conv	Like 1.5C-Elec, but with more conventional technology orientation: ● Slower technological progress in solar PV (20% learning rate resulting in capital costs of ~390 US$2015/kW in 2050) ● Low demand response resulting in higher storage requirements ● No market introduction or infrastructure policies for electric vehicles ● Bioenergy supply based on agro-economic potential (up to 300 EJ/yr), no phase out of 1st gen. bioenergy. ● Global CCS injection capacity of 20 $GtCO_2$/yr
WB2C-Conv	Like 1.5C-Conv, but cumulative 2020-2100 emissions limited to 900 $GtCO_2$
Reference	Continuation of currently implemented energy and climate policies without future strengthening of ambition
Sensitivities	Additional sensitivity scenarios varying individual 1.5C-Elec with regard to assumptions on bioenergy, CCS, variable renewable energy supply and transport electrification are described in Suppl. Table 1 and analyzed in Suppl. Figure 1.

The role of electricity in decarbonization

Future transformation scenarios agree on a continuation of the trend towards increasing shares of electricity in final energy[2,3,33]. In our reference scenario without strengthening of climate policy ambition, the electrification shares increase to 33% by 2050, consistent with other baseline scenarios[27]. Climate policy tends to accelerate this electrification trend. The SR15-1.5C-scenarios have electrification shares of 34-53% in 2050 (10th-90th percentile).

Due to the broad representation of electrification opportunities in end-use sectors, and continued technological progress in photovoltaics, wind and battery storage, resulting electrification shares in 1.5C-Elec and WB2C-Elec are 66% and 58%, respectively, in 2050, thus tracking the higher end or exceeding the range observed in the corresponding subsets of SR15 mitigation scenarios (Figure 1a). In each of the demand sectors buildings, industry and transport, electricity shares in final energy in 2050 in 1.5C-Elec are above the 90th percentile of corresponding SR15-1.5C-scenarios (Extended Data Figure 1). As energy supply is increasingly dominated by wind and solar electricity, the deep electrification of end uses is a key enabler for a dominance of non-bioenergy renewables-based final energy in the second half of the century exceeding the range of SR15-1.5C-scenarios (Figure 1b).

A sensitivity analysis (Suppl. Figure 1) shows that the reduced availability of biomass and CCS and the accelerated penetration of battery-electric vehicles in transport contribute in similar ways to the high electrification shares observed in the 1.5C-Elec scenario. Assumptions about integration costs and PV cost degression mostly affect the share of solar power in power generation, but only to a lesser extent the degree of electrification.

The comparison with the SR15 scenario data further shows that 1.5C-Elec and WB2C-Elec are characterized by a low share of fossils in primary energy, and lower reliance on CDR due to the limitations on bioenergy and CCS (Figure 1c).

The electrification scenarios are also characterized by relatively low final energy demands despite continued growth of economic activity. Final energy demand in 2050 in Elec-1.5C is slightly lower than today, and lower than in most SR15-1.5°C-scenarios. This is because electricity is a high-exergy energy carrier – i.e., one unit of electricity can provide more work than one unit of fuel or heat. For instance, the socket-to-wheel efficiency of electric cars is around 80%, compared to a below 30% tank-to-wheel efficiency for combustion engines[34]. Electric heat pumps for space heating or low temperature process heat typically have a coefficient of performance of three or higher, thus each kWh of electricity provides at least 3 kWh of thermal energy. Secondary steel production from scrap steel in electric arc furnaces (EAF) decreases energy inputs compared to conventional steel production in blast furnaces by up to a factor of ten[35].

The share of electricity in final energy therefore tends to even understate the contribution of electricity to the provision of energy services and materials. Beyond final energy demands, the transition to wind- and solar-based electricity further reduces primary energy demands since it all but eliminates the energy conversion losses of thermal power plants.

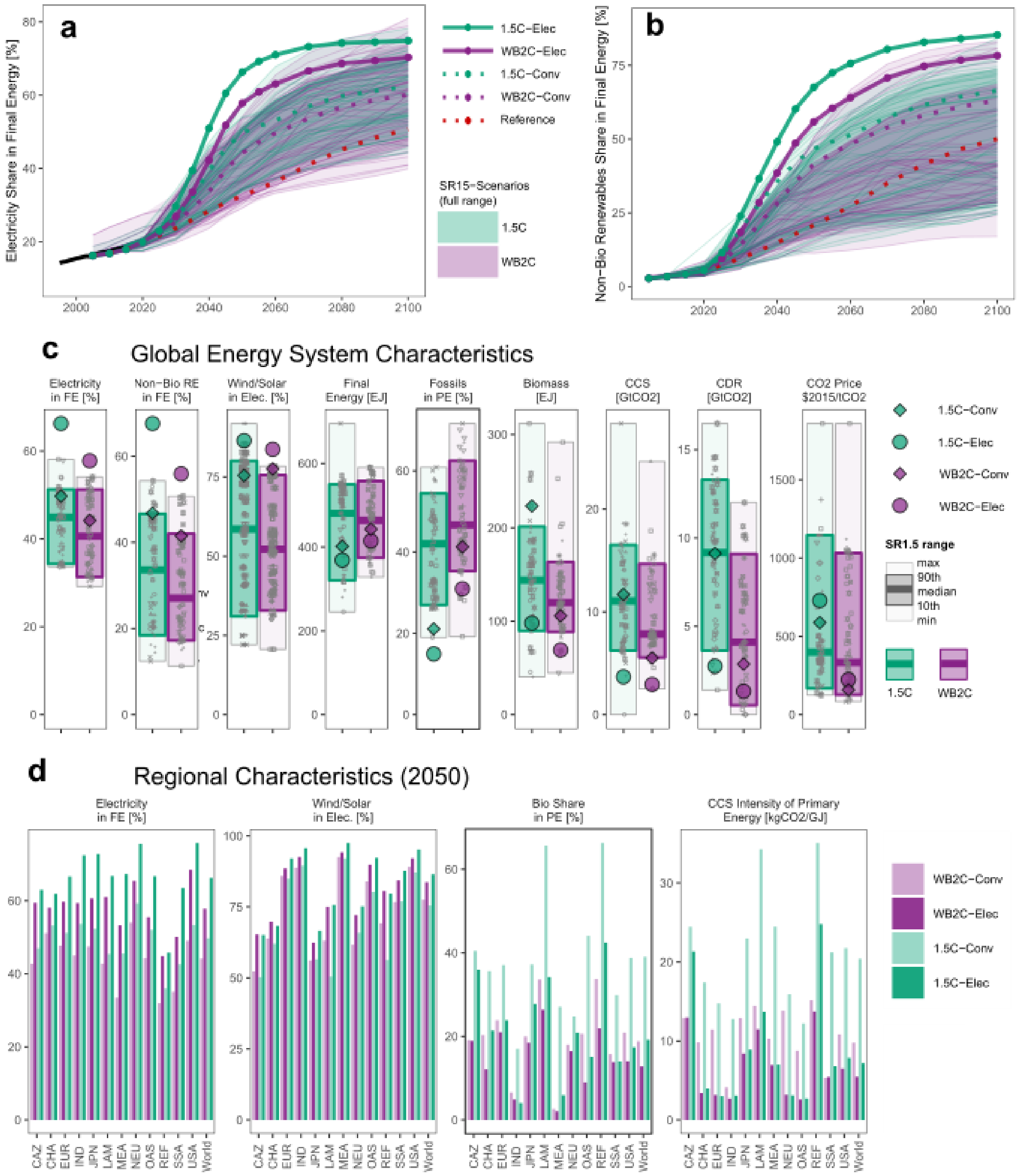

Figure 1 | Key characteristics of renewables-based electrification and conventional scenarios. Evolution over time of (a) the share of electricity in final energy, and (b) contribution of non-biomass renewables to final energy via electricity, district heating systems with heat pumps and green hydrogen. (c) Additional key scenario indicators in comparison to scenarios assessed in the IPCC SR1.5 scenario database. Purple and green shading in a-c indicate full range (light), 10th-90th percentile (dark), and central bars the median of lower 2°C and 1.5°C-scenarios from the SR1.5 (see Methods for details). (d) Comparison of scenario characteristics across regions (see Methods for region definitions).

Economic drivers of electrification

The high electrification observed in mitigation scenarios is driven by a fundamental shift in the energy price structure due to carbon pricing and technological progress. Historically, energy systems were based on the principle that electricity is a precious energy carrier that is substantially more expensive than combustible energy carriers. We find that in a low-carbon future the price ratio between electric and non-electric energy will decrease, and is likely to even reverse in the long term. The reason is two-fold: first, prices for solid, liquid and gaseous fuels for end uses without CCS will increase in line with the ever-increasing carbon prices required to keep the Paris Climate targets as long as biomass is insufficiently available to fully substitute fossils. Second, innovation in solar, wind and battery technology continues to reduce costs and is thus the main enabler of a decoupling of electricity prices from increasing carbon prices.

This is illustrated in Figure 2, which shows the price development of various secondary energy carriers in the WB2C-Elec, 1.5C-Elec and Reference scenarios. Without strengthening climate policies (Reference), future price developments are mostly determined by the gradual increase of fossil extraction costs. In the WB2C-Elec and 1.5C-Elec scenarios, the introduction of carbon pricing in 2025 leads to a substantial initial increase of electricity prices, as electricity generation is still dominated by fossil power. Global average electricity prices decrease after 2025 to below 80 US$2015/MWh by 2035, due to the progressing decarbonization of power supply (Extended Data Figures 2, 3). Importantly, and consistent with prior findings[30], direct solar PV generation costs fall to around 10 US$2015/MWh in all world regions with the exception of Japan by 2050 (Suppl. Figure 2). However, substantially higher system level costs are incurred due to curtailment of excess variable renewable electricity (VRE) generation and firming requirements (Suppl. Figure 3).

In contrast to electricity, energy prices for carbonaceous fuels continue to increase (Figure 2). In the case of 1.5C-Elec, global average electricity prices are surpassed by liquids around 2030, by gases in 2035, and solids in 2040. While the price advantage of electricity in the long-term is robust across mitigation scenarios, it occurs somewhat later in the WB2C-Elec, 1.5C-Conv and WB2C-Conv scenarios (Figure 2). Electricity as a precious high-exergy energy carrier thus becomes the cheapest, with profound implications for energy systems.

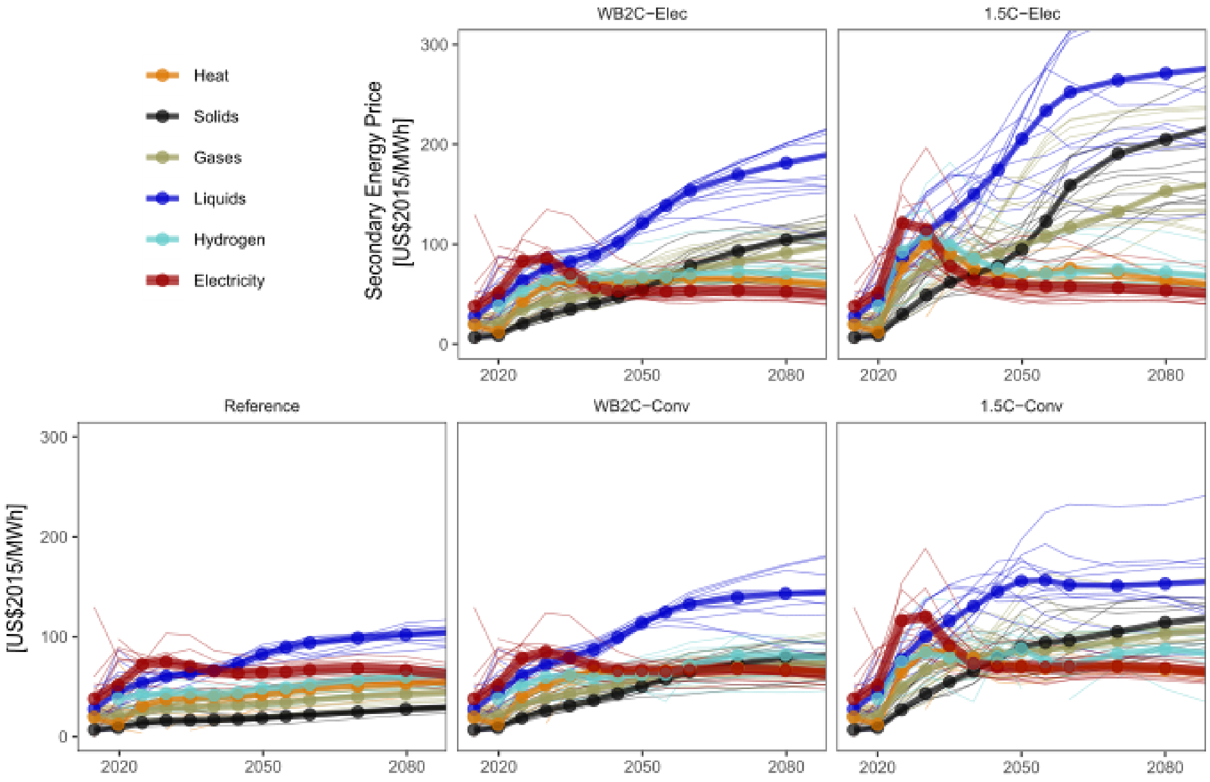

Figure 2| Evolution of energy prices at the secondary energy level. Thick solid lines indicate global averages, thin lines results for individual model regions. Electricity becomes the cheapest energy carrier by 2040 in 1.5C-Elec and 2050 in WB2C-Elec. Electricity prices represent the full-system prices, thus accounting for costs for storage technologies and curtailment. Note that the prices shown here account for carbon prices, but not distribution costs, end-use taxes etc.

Energy systems implications

Figure 3, Extended Data Figure 4 and Suppl. Figures 4-6offer a perspective on the transformations in global energy supply systems in the 1.5C-Elec and WB2C-Elec scenarios. 1.5C-Elec results in a 3.5-fold increase of electricity generation by 2050 relative to 2015, and an around 6-fold increase until the end of the century (Figure 3a). VRE from wind and solar power, driven by continued technological progress and cost reductions as well as carbon pricing of fossil competitors, dominates electricity supply. Hydropower expands modestly, but its resource potential is more limited than that of wind and solar power. Nuclear power is phased out gradually, largely due to the lack of competitiveness with wind and solar power. All mitigation scenarios are characterized by a rapid phase-out of fossil-based power generation. Coal fired power falls below 1% of generation by 2035, fossil gas fired power follows by 2050 in the 1.5C-Elec scenario.

These key results regarding the role of electricity and renewables are robust across world regions (Figure 1d), despite structural differences in sectoral energy demands and primary energy resource endowments (Extended Data Figure 5). For 1.5°C-Elec in 2050, we find that wind and solar power accounts for at least 65% of power generation by 2050, and that electricity becomes the cheapest energy carrier in all world regions by 2050, accounting for more than 60% of final energy in all regions with the exception of the reforming economies (REF) of the Former Soviet Union, for which bioenergy and carbon storage potential are somewhat less constrained.

The integration of VRE requires substantial effort and is accomplished through a combination of grid expansion for interregional pooling, battery storage for balancing short-term mismatches between supply and demand, flexibilized energy demands and hydrogen generation, and curtailment of surplus VRE generation (see Methods for details and Suppl. Figure 7 for indicators).

Hydrogen generation has strong synergies with VRE integration. It allows to store excess VRE electricity, which reduces curtailment, as well as to produce hydrogen at low-cost by making use of flexible operation of proton-exchange-membrane electrolysis at times of low electricity prices from VREs. Hydrogen is a valuable by-product of a strong VRE expansion and can be used to further reduce the use of carbonaceous fuels in the demand sectors, and for re-electrification at times of low VRE supply. As hydrogen is mostly produced from electricity (Suppl. Figure 6), hydrogen use can be considered an indirect form of electrification. End-use sectors consume 12 EJ of hydrogen in 2050 and 47 EJ in 2100 in the 1.5C-Elec scenario.

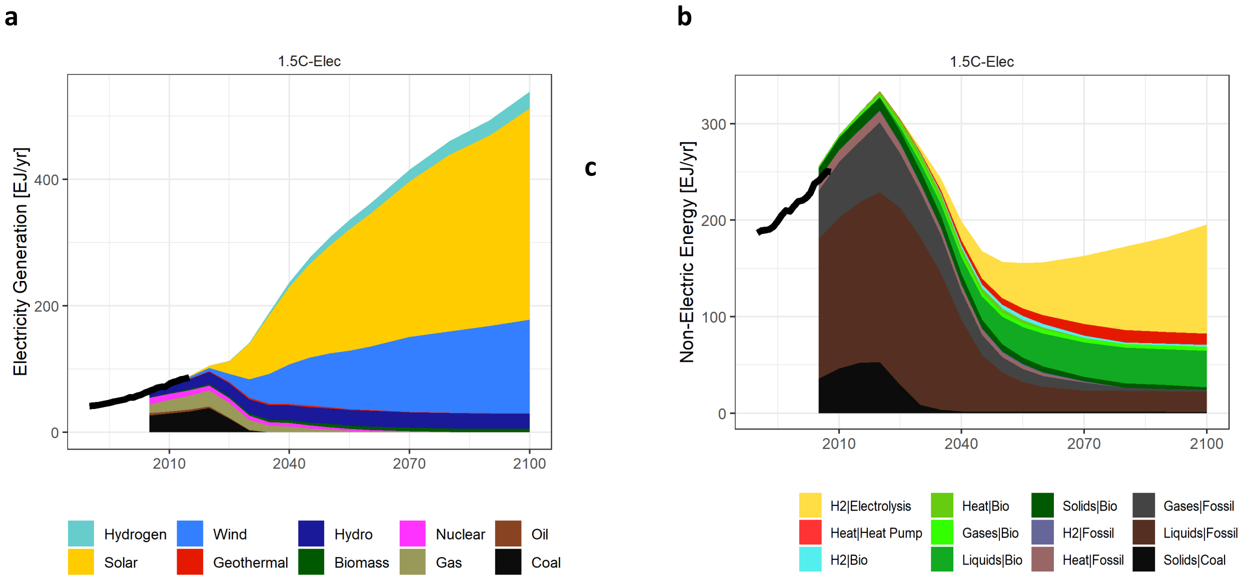

Figure 3| Energy supply system developments in 1.5C-Elec scenario. (a) Electricity generation, (b) non-electric secondary supply by primary energy source. Heat on the secondary energy level refers to heat supply for district heating, excl. decentral heating in the industry and buildings sectors.

End-use sectors

The remaining carbonaceous final energy demand in 2050 in 1.5C-Elec amounts to around 98 EJ in 2050 and 68 EJ in 2100 (Figure 4a). It is mostly supplied from bioenergy and petroleum (Figure 3b). A closer look at the breakdown of remaining carbonaceous energy demands by end-use sectors provides an indication of electrification opportunities and bottlenecks.

In transportation, technological progress in battery technology is the key enabler of electrified mobility. Increasing economic competitiveness as well as consumer acceptance due to market introduction policies (see Methods) leads to a rapid transition towards battery electric vehicles (BEVs) in the light duty vehicle sector, resulting in a close to 100% share in the global car fleet by 2050 (Figure 4b,c).

Electric drivetrains in combination with batteries or fuel cells are also becoming increasingly competitive for trucks. Consequently, almost all road-based freight transportation services become electrified via battery or fuel-cell technology in the 1.5C-Elec scenarios by mid-century.

Remaining hydrocarbon fuel use in the transport sector is dominated by aviation and shipping (Suppl. Figure 8). For aviation, electricity-based or hydrogen-based propulsion concepts are conceivable[36], but will take decades to develop and may only become available for short-distance travel, which only accounts for a fraction of the fuel consumption[36]. Hydrogen or ammonia are considered zero-carbon fuels for shipping[37,38], but thus far have low technological maturity. Given these barriers and relatively slow innovation cycles in aviation and shipping, REMIND only represents conventional technology based on hydrocarbon fuels. In 1.5C-Elec, aviation and shipping account for a combined liquid fuel demand of 27 EJ in 2050, 10 EJ of which are supplied from bioenergy.

Even in the absence of climate policy, there is a strong trend towards electricity-based end uses in the buildings sector[39], resulting in an increase of electrification from 32% in 2015 to 54% in 2050 and 78% in 2100 in the Reference scenario (Suppl. Figure 9). Most of the energy demand growth is due to appliances and air conditioning, while efficiency improvements and satiation of energy service demands lead to a stabilization of energy demands for space heating, water heating and cooking despite increasing affluence. Electrification accelerates to an 88% share in the 1.5C-Elec scenario in 2050 (Extended Data Figure 1). This enhanced electrification is mostly driven by a transition from burners to electrical heat pumps for space and water heating.

Electrification of industry energy demands is comparatively low. Remaining carbonaceous fuel demands in industry are dominated by chemicals (22 EJ in 1.5C-Elec in 2050, Suppl. Figure 10). Feedstocks cannot be directly substituted with electricity and account for more than half of the sector's final energy demand, limiting electrification in the chemical industry to around 40% in 2050 (Figure 4e). This suggests that by 2050 the bottleneck for the electrification of the chemical sector is limited mostly to fuels for non-energy uses.

The electrification of steel reduces the carbonaceous fuels consumption in the most CO_2-intensive industry sector to 2 EJ by 2050 and is driven by the substitution of primary with secondary steel. By mid-century, 82% of the global steel is supplied via electric melting of scrap (Figure 4d), halving energy demand per ton of steel compared to 2020. Cement and other industry subsectors account for an additional 21 EJ of residual carbonaceous fuels in 2050 in 1.5C-Elec.

Indirect electrification via hydrogen becomes an increasingly relevant option in the long-term. Hydrogen can substitute natural gas, coke and coal (e.g. in ammonia synthesis and iron reduction) or be used to synthesize chemical feedstocks. Hydrogen contributes 11 EJ to the industrial energy demand in 2050 and 25 EJ in 2100 in the 1.5-Elec scenario (Suppl. Figure 10).

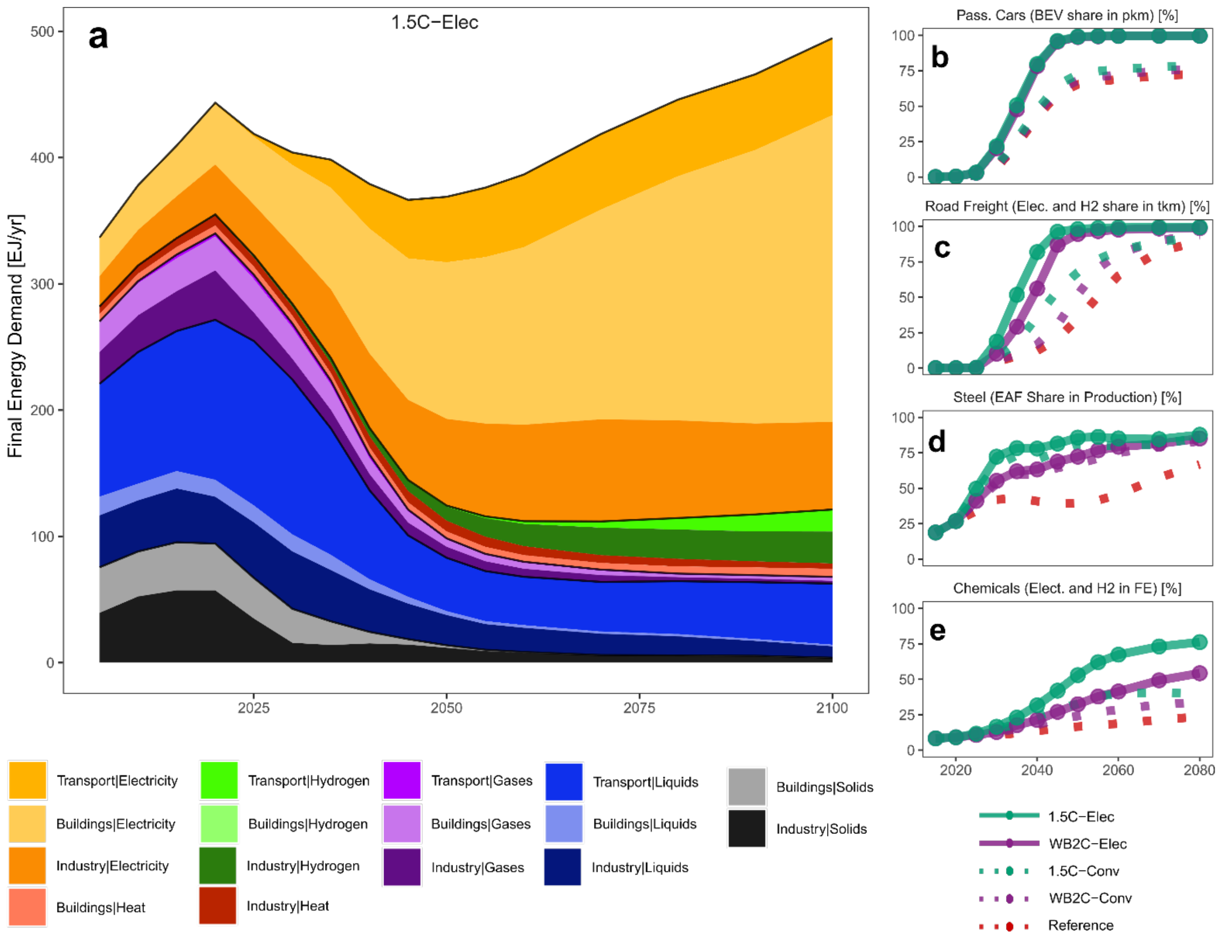

Figure 4| Final energy demand and energy services in electrification scenarios. (a) Final energy in 1.5C-Elec by energy carrier and end-use sectors. (b) Electrification shares of crucial end-uses passenger cars (share of Battery Electric Vehicles in passenger-kilometers of cars), road freight (share of electric (including via fuel cell) trucks in ton-kilometres), steel (share of EAF in steel production volume), chemicals (share of electricity and hydrogen in final energy, including feedstocks).

Economic and environmental implications

For both the 1.5-Elec and 1.5C-Conv scenarios, the aggregate costs of climate change mitigation in terms of losses in aggregate discounted 2020-2050 GDP amount to less than 2% (Figure 5). The sensitivity analysis in Suppl. Figure 1 shows that the cost impact of limited bioenergy and CCS slightly exceeds the benefit of deep electrification of transportation and, to a lesser extent, technological progress in solar PV and VRE systems integration. The GDP losses are highest for the resource exporting regions Middle East (MEA) and Reforming Economies (REF, Former Soviet Union), as well as the fast growing economies of India (IND), China (CHA), Other Asia (OAS) and Sub-Saharan Africa (SSA) (Figure 5a). 1.5C-Elec features lower GDP losses compared to 1.5C-Conv for solar rich SSA, while those for REF and CHA are slightly higher.

The decreased reliance on bioenergy in the 1.5C-Elec case has strong implications for environmental side-effects of climate change mitigation (Figure 5b). This is particularly evident for land and water demands. In 2050, 370 Mha of bioenergy cropland are required in 1.5C-Conv, compared to 140 for 1.5C-Elec. By contrast, despite the much larger wind and solar power generation, land requirements for non-biomass electricity in 1.5C-Elec are only slightly greater than in 1.5C-Conv. This is consistent with earlier findings[8,40] of much greater per-unit area demands of bioenergy compared to wind and solar power. Similarly, additional irrigation water consumption induced by climate policies is 450 km³/yr higher in 1.5C-Conv compared to 1.5C-Elec, while differences across scenarios in non-bioenergy water consumption of the energy system amount to 6 km³/yr. Reduced bioenergy demand also reduces the pressure on food prices in the 1.5C/WB2C-Elec scenarios compared to corresponding 1.5C/WB2C-Conv scenarios. On the other hand, the high wind and solar capacities required in renewables-based electrification pathways also exacerbates metal depletion induced by the energy sector.

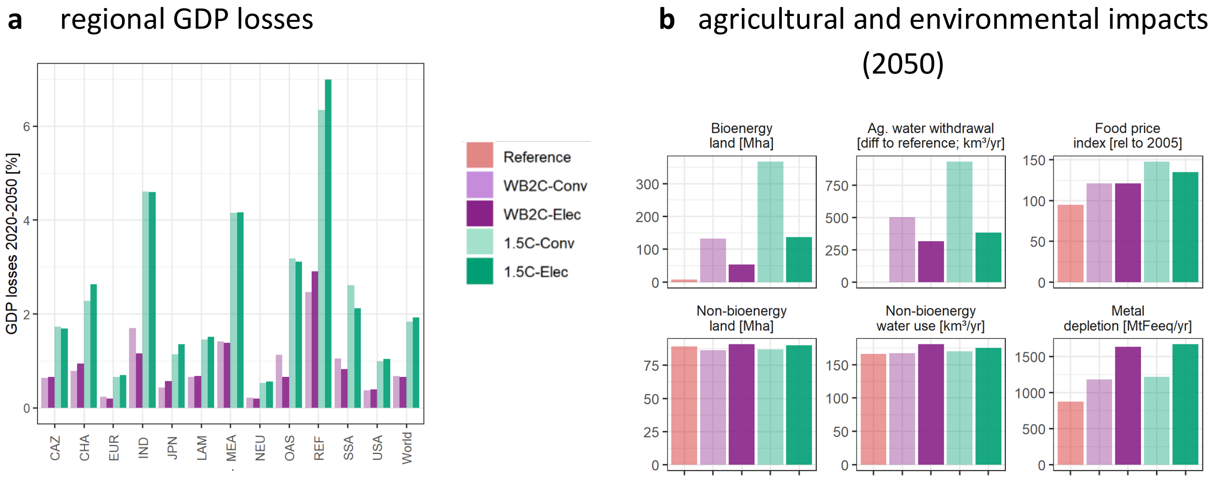

Figure 5| Economic and environmental implications. (a) Regional mitigation costs in terms of aggregate GDP differences relative to Reference scenario from 2020-2050 (discounted at 5% p.a.). (b) Impacts in 2050: Agricultural impacts of bioenergy derived from land-use modeling (upper row) and environmental impacts of non-bioenergy derived from prospective life-cycle assessment (see Methods). Agricultural water use is displayed as difference to the *Reference* scenario.

Conclusions and discussion

A profound and rapid energy transformation is required to put the world on a pathway for limiting warming in line with the climate targets of the Paris Agreement. Despite the low overall ambition of global climate action until now, formidable technological progress in solar PV, wind power and battery technologies have been among the most encouraging developments towards this transformation. Renewable electricity supply is already cost-competitive in many parts of the world, and electric vehicle technology is making rapid strides towards increasing competitiveness. At the same time, the sustainability and regulatory challenges of large-scale bioenergy use are becoming increasingly evident[41,42] and so are difficulties in upscaling carbon capture and storage[43–45].

Against this background, a climate change mitigation strategy centered around renewables-based electrification becomes increasingly plausible. Our analysis shows that climate policy strongly shifts the economics in favor of electricity as an energy carrier, and especially so in a world with constraints on bioenergy and CCS availability. The detailed analysis of individual end uses also reveals greater demand-side electrification potential than suggested in the previous integrated assessment modeling literature. The increasing electrification of end uses makes it possible to tap into the large potential of wind and solar for hitherto non-electric energy demands. Fuel demands for aviation, shipping, some industrial processes as well as feedstocks for the chemical industry are the most significant sources of residual demands for carbonaceous energy carriers.

The scenarios presented here provide examples of possible pathways into a low-carbon future, but many others are conceivable. Importantly, in addition to continued rapid technological change in wind, solar and battery technology, the key enabling assumptions for very high electrification shares in our scenario are (1) limited biomass, (2) limited CCS, and (3) limited other CDR options. In turn, this means that the level of electrification will be lower if more biomass is available, or with greater CCS potential. On the other hand, electrification shares could become even higher in the long-term with further technological breakthroughs, e.g. in battery technology, in aviation, primary steel production or other industrial processes. There is also substantial scope for further indirect electrification via synthetic electricity-based hydrocarbons[34,46], which were not considered as part of this study.

Finally, the transition to a renewables-based electrification of energy supply and demand is only possible in a favorable policy environment. First and foremost, comprehensive carbon pricing is crucial for internalizing the climate benefits of renewable electricity vis-a-vis fossil-based fuels. Secondly, the increasing share of VRE in power supply requires adjustments of the electricity market design to incentivize deployment of storage and flexibilization of demand. Thirdly, a deep electrification of energy systems requires political coordination in the build-up of new infrastructure, such as grid interconnectors to pool VRE generation over larger geographical areas, or charging stations for electric vehicles, as well as public acceptance for the deep systems transformations involved. The energy transition is a tremendous opportunity for climate change mitigation, for the broader sustainable development agenda and for investors - however, determined action by policymakers and broad public support is necessary to seize it.

Methods

REMIND-MAgPIE Integrated Assessment Modeling Framework

We use the Integrated Assessment Model REMIND[23] (REgional Model of Investment and Development) in its version 2.1.3 in combination with the MAgPIE land use model (Ref. [28] and section "Land-use Modeling" below) to generate the scenarios presented in this paper. REMIND models consistent evolutions of the global energy-economy-climate system. REMIND represents 12 subregions, namely the European Union (EUR, including the United Kingdom), four individual countries (CHA - China; IND - India; JPN - Japan; USA - United States of America), and seven aggregate regions (CAZ -Canada, Australia, New Zealand; LAM - Latin America; MEA - Middle East and Africa; NEU - Non-EU Europe; OAS - Other Asia; REF - Russia and other reforming economies; SSA - Sub-Saharan Africa)). REMIND is solved for the 2005-2150 time span in 5-year timesteps of 5 years from 2005-2060 and 10 year timesteps thereafter. By default, the model is run in intertemporal optimization, implying perfect foresight by agents. Since the finite time horizon induces distortions in the investment behavior of the final time steps, we restrict the evaluation of results to the time horizon until 2100.

REMIND couples an intertemporal macro-economic growth model with a detailed energy system representation, including substantial detail in energy demand technologies providing services and materials in the transport and industry sectors. An important feature distinguishing REMIND from other global energy-economic models such as MESSAGE[47] or TIAM[48] is the formulation as a non-linear optimization problem. This allows accounting for crucial non-linearities, such as endogenous technological change[49], non-linear macro-economic production functions driving energy demand[50], or the non-linear increase of integration challenges with increasing shares of VRE[51]. A short overview of the key components of the model is given in the following paragraphs. The model code is available open source at https://github.com/remindmodel and further documented at https://rse.pik-potsdam.de/doc/remind/2.1.3/.

The macro-economic core of REMIND is an investment model maximizing welfare over time, subject to equilibrium conditions and system constraints. Aggregate economic output is calculated from a constant elasticity of substitution production function with capital, labor and energy as input factors. In terms of its macro-economic formulation, REMIND resembles other well established integrated assessment models such as RICE[52] (Regional Integrated Climate-Economy) and MERGE[53]. However, REMIND is broader in scope and features a substantially higher level of detail in the representation of energy-system technologies, trade, and global capital markets. For the scenarios presented here, the model optimizes regions individually and uses an iterative adjustment mechanism to clear international markets for (primary) energy carriers and non-energy goods[54].

Energy System Modelling

The energy supply system in REMIND represents the conversion of primary energy carriers into secondary energy carriers and their transport and distribution to end-use sectors. The energy system further accounts for system inertias and path dependencies induced by aging capital stocks, e.g. in power-plant infrastructure and endogenous learning-by-doing. Additionally, REMIND accounts for challenges related to rapid upscaling of new technologies via cost-markups that are assumed to increase with the square of year-to-year capacity additions[55]. The REMIND model represents the endowments of exhaustible primary energy resources[56] as well as renewable energy potentials based on bottom-up estimates[23,57,58]. REMIND accounts for cost reductions in solar photovoltaics, concentrating solar power, wind energy and battery storage endogenously via learning-by-doing. Technological progress for all other technologies is parameterized via exogenous assumptions.

The REMIND model captures the challenges and options related to the temporal and spatial variability of wind and solar power[57]. In addition to flexible demand response, also inter-regional pooling as well as short-term storage (diurnal time-scales, mostly via batteries) and long-term storage (up to seasonal time-scales) play a key role for facilitating VRE integration. REMIND parameterizes corresponding technology and region-specific VRE storage and grid expansion requirements[51] as well as curtailment rates (i.e., unused surplus share of VRE electricity generation), which are derived with the help of two detailed electricity production cost models[51,59]. These integration challenges per unit VRE generation increase disproportionately with increasing shares of VRE in total electricity generation. In the 1.5C-Elec and WB2C-Elec scenarios we assume short-term battery storage demands at a given VRE share to be half of those in the corresponding Conv scenarios, reflecting recent findings[60,61] of the substantial potential of flexible demand response from vehicle-to-grid and power-to-heat applications. In 2050, resulting costs associated with electricity storage and grid expansion amount to roughly 10-20 US$2015 per MWh for solar PV (Suppl. Figure 3) and curtailment rates are 10-30% for solar and 0-10% for wind electricity generation in the 1.5C-Elec scenario. The variations reflect differences in regional wind and solar electricity shares as well as the matching of demand and renewable supply profiles. In the 1.5C-Elec and WB2C-Elec scenarios, we assume that about half of the diurnal flexibility requirements can be met by flexibilized electricity demand. The remaining flexibility is provided by short-term battery storage and long-term hydrogen storage (electrolysis and hydrogen turbines). In addition, operating reserve requirements are represented similarly to a flexibility balance equation[62].

Energy End Uses

An important feature of this study is the representation of demand sectors and related electrification potentials, which is more detailed than in most previous integrated assessment studies. In the industry sector, REMIND represents four subsectors: steel, cement, chemicals and other manufacturing. Both primary (virgin) steel production from iron ore and secondary steel production from scrap are represented via a simplified stock-flow-model based on Pauliuk et al.[63]. Energy demand in these subsectors is broken down into heat demands, mechanical work and feedstocks. Mechanical work is already electrified, or can be readily electrified in the future. We further consider indirect electrification of the high-temperature heat inputs for primary steel, cement production and chemical industry via hydrogen. The substitution of heat supply from non-electric to electric energy in other manufacturing is represented via a constant elasticity of substitution production function. Feedstocks in the chemical industry must be supplied as hydrocarbon fuels.

Concerning the transport sector, for this study we adopt the coupled system REMIND/EDGE-T[25] to analyze the electrification potential in detail. Mobility is divided into passenger and freight demands, each broken down by trip length into long-distance and short-medium distance components. The market for each transport demand category is split across different transport modes and vehicle types. Multiple technology options are available for each vehicle type: electricity can be consumed directly in battery electric cars, buses and trucks, and electric trains. Indirect electrification via hydrogen is available for all road transport options. For passenger cars, mode choice accounts for the value of time of alternative modes. In addition, the technology choice module accounts for dispreferences, e.g., due to range anxiety or low model availability in the case of BEVs. In the 1.5C-Elec and WB2C-Elec scenarios, we assume an accelerated build-up of charging infrastructure and a subsidy program between 2021-2035. These interventions result in an elimination of the dis-preference of BEVs vis-a-vis combustion engine cars by 2035. In contrast to road transportation, aviation and shipping can only rely on liquid fuels, given technological obstacles to switching to other propulsion systems[36,64].

Transformation pathways for buildings energy demand are derived from the EDGE-Buildings model for the baseline (or no-policy) development, and from the detailed buildings module of REMIND for the policy response. The EDGE-Buildings[23,58] model projects energy service demands for the subsectors (i) space heating, (ii) water heating, (iii) cooking, (iv) space cooling, and (v) appliances and lighting, based on exogenous socio-economic and climate pathways. The REMIND buildings module is then calibrated to meet these energy service trajectories, and represents technology choice to meet these service demands. Non-electric energy demands are only relevant for space and water heating and cooking, whereas space cooling and appliances/lighting are fully reliant on electric energy. REMIND represents resistance heating and heat pumps as options for electrifying these demands.

Beyond energy-related CO_2, REMIND further represents a wide spectrum of greenhouse gas emissions. CH_4 emissions from fossil resource extraction are represented by source. REMIND is coupled to the MAgPIE4.0 land use model[28] to derive CO_2 emissions from land use, land use change and forestry, as well as CH_4 and N_2O emissions from agricultural activities. Abatement options for CH_4 and N_2O emissions from energy supply, agriculture, waste and wastewater are based on marginal abatement cost curves from Harmsen et al.[65]. Emissions from fluorinated gases are represented exogenously from Van Vuuren et al.[66] Emissions from aerosols and short-lived trace gases are based on the GAINS model[67]. Our modelling framework employs the MAGICC[68] reduced complexity climate model in its version 6.3 to evaluate the resulting changes in global climate variables from the emerging emission scenarios. The impacts of climate change on energy systems and the economy are not considered in the modeling.

Land-Use Modeling

To account for land- based mitigation options and their interactions with the energy transition, REMIND is operated in coupled mode with the land use model MAgPIE (Model of Agricultural Production and its Impact on the Environment)**[28]**. The coupling ensures a market equilibrium between bioenergy demand and bioenergy supply as well as accounting for other land-based mitigation options. It further allows to derive environmental implications of bioenergy production. MAgPIE is a global partial equilibrium model of the land-use sector that operates in a recursive dynamic mode and incorporates spatially explicit information on biophysical constraints into an economic decision making process[69]. It is frequently used to assess the competition for land and water, and the associated consequences for sustainable development under future scenarios of rising food, energy and material demand, climate change impacts, and land-related greenhouse gas mitigation policies. It considers regional economic conditions, such as demand for agricultural commodities, and spatially explicit data on biophysical constraints. Spatially explicit data on biophysical conditions are provided by the Lund-Potsdam-Jena managed land model (LPJmL)[70,71] on a 0.5 degree resolution and include e.g. carbon densities of different vegetation types, agricultural productivity such as crop yields and water availability for irrigation. Due to computational constraints, all model inputs in 0.5 degree resolution are aggregated to simulation units for the optimization process based on a clustering algorithm[72]. Land types in MAgPIE include cropland, pasture, forest, other land (including non-forest natural vegetation, abandoned agricultural land and deserts) and settlements. Cropland (rainfed and irrigated), pasture, forest and other land are endogenously determined, while settlement areas are assumed to be constant over time. The cropland covers cultivation of different crop types (e.g. temperate and tropical cereals, maize, rice, oilseeds, roots), both rainfed and irrigated systems, and two second generation bioenergy crop types (grassy and woody). Considering international trade based on historical trade patterns and economic competitiveness, global production has to meet demand for food, feed, seed, processing and bioenergy. Food demand is derived based on population growth and dietary transitions, accounting for changes in intake and food waste, the shift in the share of animal calories, processed products, fruits and vegetables as well as staples. MAgPIE estimates flows of different greenhouse gases (GHGs) from land use and land-use change. CO_2 emissions are calculated based on changes in carbon stocks of vegetation, which are subject to land-use change dynamics such as conversion of forest into agricultural land[73]. In case of afforestation or when agricultural land is set aside from production, regrowth of natural vegetation absorbs carbon from the atmosphere (negative CO_2 emissions). Nitrogen emissions are estimated based on nitrogen budgets for croplands, pastures and the livestock sector[74]. CH_4 emissions are based on livestock feed and rice cultivation areas[75]. In climate policy scenarios, GHG emissions are subject to pricing, thus affecting decision-making regarding land use, land expansion as well as prices for bioenergy and non-energy crops.

To derive environmental impacts from non-biomass electricity generation, we integrated scenario results with prospective life-cycle analysis using the *premise* framework[76]. In this way, the underlying life-cycle database Ecoinvent[77] is expanded to account for the feedback of the energy transition on production systems. The life-cycle impact assessment is based on ReCiPe[78].

Scenario design

The Reference policy scenario assumes a continuation of energy and climate policies that are currently implemented on the national level, without future strengthening of ambition. These policies include various targets for the years 2020-2025 backed by legislation, with respect to emissions, technology deployment, efficiency, and shares of low-carbon energy.

The climate stabilization scenarios limit cumulative CO_2 emissions from 2020 until time of net-zero CO_2 emissions to 500 $GtCO_2$ (1.5C-Elec, 1.5C-Conv), and 900 $GtCO_2$ (WB2C-Elec, WB2C-Conv), respectively. The peak budget[79] is represented in REMIND by a specific shape of the carbon price trajectory, with a steep linear increase in the front-runner regions (those with per-capita GDP > 24000 US$ in 2015) until the net-negative emissions are reached, and a further slow linear increase of carbon prices at 3 US$ per year thereafter to maintain below-zero global CO_2 emissions. The carbon prices in poorer regions only gradually converge towards the level of the front-runner regions in 2050 to avoid disruptive economic impacts of high carbon pricing in earlier stages of development. The ratio of the regional carbon price in 2025 compared to the front-runner depends on the per-capita GDP bin of the respective country region in 2015, with the poorest countries with a per-capita GDP of below 3000 US$/cap starting at 10%, and convergence being prescribed by a quadratic function reaching 100% in 2050. The timing of the year of reaching net zero emissions, as well as the required carbon price in that year, are endogenously determined based on the peak-budget value via iterative adjustment. Resulting regional carbon prices are shown in Suppl. Figure 13. Thereby scenarios with high overshoot of the carbon budget around mid-century and large reliance on CDR in the second half of the century - which are common when CO_2 budgets are only specified for the year 2100 - are avoided.

Comparison to existing integrated assessment modeling literature

The comparison of the scenarios with the pre-existing integrated assessment modeling literature was facilitated the SR1.5 scenario database hosted by the International Institute for Applied Systems Analysis (IIASA) through a process facilitated by the Integrated Assessment Modelling Consortium (doi: 10.5281/zenodo.3363345 | url: data.ene.iiasa.ac.at/iamc-1.5c-explorer). This database was created for the scenario assessment of the IPCC Special Report on Global Warming of 1.5°C.

We used carbon price levels in 2050 and 2100 as a proxy of techno-economic implementation challenges, and excluded scenarios with $p_{CO2} > 2000$ \$/tCO_2 in 2050 to exclude pathways with extremely high implementation costs. The resulting data set includes 54 pathways from 7 models categorized as 'Below 1.5C', '1.5C low overshoot', '1.5C high overshoot' - here referred to as *SR15-1.5C-scenarios* - and 64 pathways from 12 models categorized as 'Lower 2C' scenarios (*SR15-WB2C-scenarios)*. Note that our study assumed socio-economic developments following the SSP2 (“middle-of-the road”) narrative and assumptions[80], while the SR1.5 set also encompasses other SSPs.

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Data availability:

The specific model runs and scenario data for this study are archived at Zenodo under http://doi.org/10.5281/zenodo.5546598 under a CC-BY-4.0 license.

Code availability:

The REMIND code is available under the GNU Affero General Public License, version 3 (AGPLv3) via GitHub (https://github.com/remindmodel/remind, last access: 30 June 2021). The technical model documentation is available under https://rse.pik-potsdam.de/doc/remind/2.1.3/ (last access: 1 December 2020). The source code and input data of MAgPIE 4.3.1 (https://github.com/magpiemodel/magpie) are openly available at http://doi.org/10.5281/zenodo.4231467. The technical model documentation is available under https://rse.pik-potsdam.de/doc/magpie/4.3.1/.

Author Contributions:

GL designed the research together with FU, RP, EK. GL, SM, LM, FU, MP, RP, MR, FS, NB, LB, CB, AD AL, AP, RR, JS, EK contributed to developing the energy-economy modeling; AP, FH and LM contributed the land-use modeling. SM, LM, MP, MR performed scenario modelling. GL, MP, FS performed data analysis and created the figures. GL wrote the paper with input and feedback from all authors.

Competing Interests:

The authors declare no competing interests.

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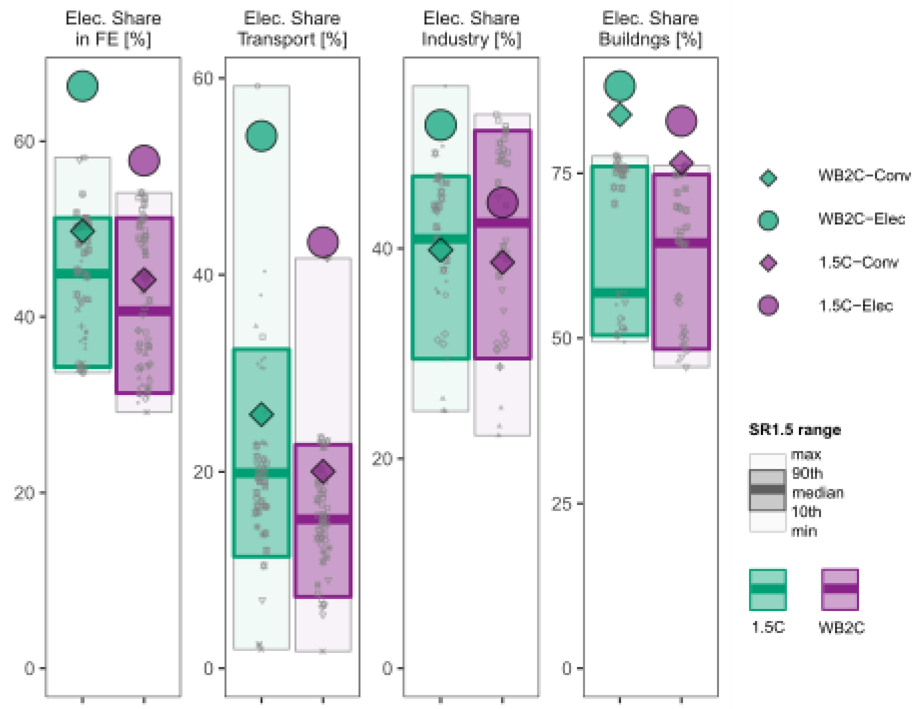
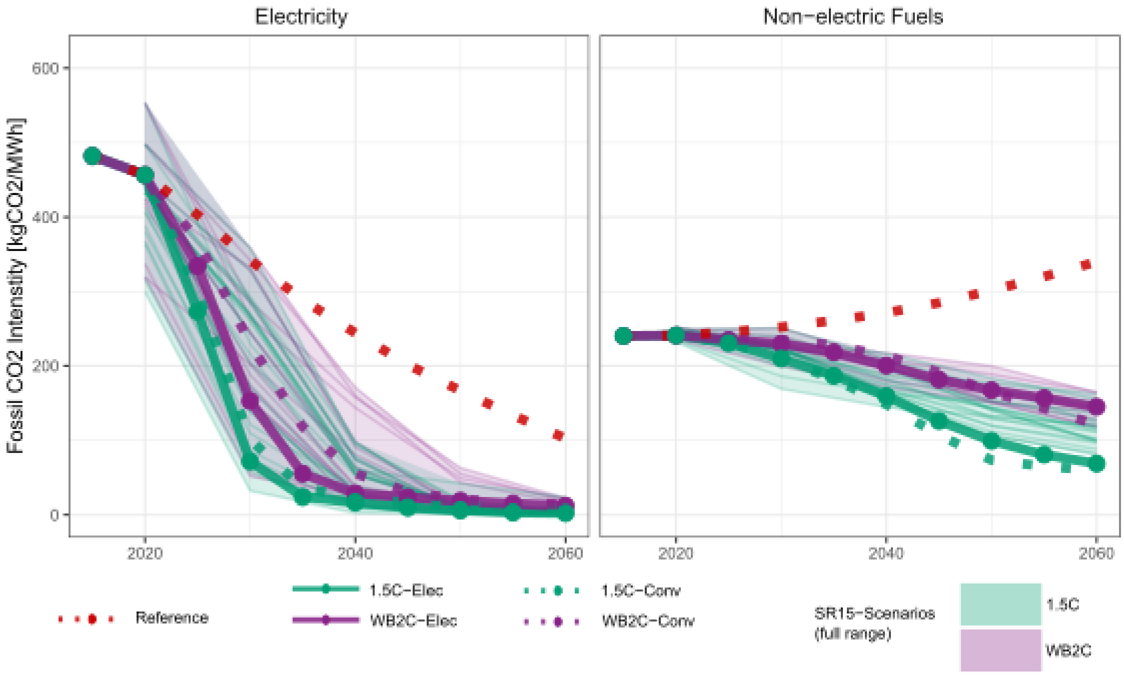
Extended Data Figures



770 **Extended Data Figure 1|Sectoral electrification shares in 2050.** Electrification shares in the transport, buildings and industry sectors in 1.5C-Elec and WB2C-Elec compared to overall electrification and electrification in corresponding IPCC SR15 scenarios.



775 **Extended Data Figure 2| Fossil carbon intensity of electricity and non-electric fuels (incl. hydrogen).** Fossil carbon intensity excludes negative emissions from BECCS. Thick solid and dashed lines indicate scenarios from this study, thin lines and shading corresponding SR15 scenarios. In all scenarios, the fossil carbon intensity of electricity declines much faster than the fossil carbon intensity of non-electric fuels.

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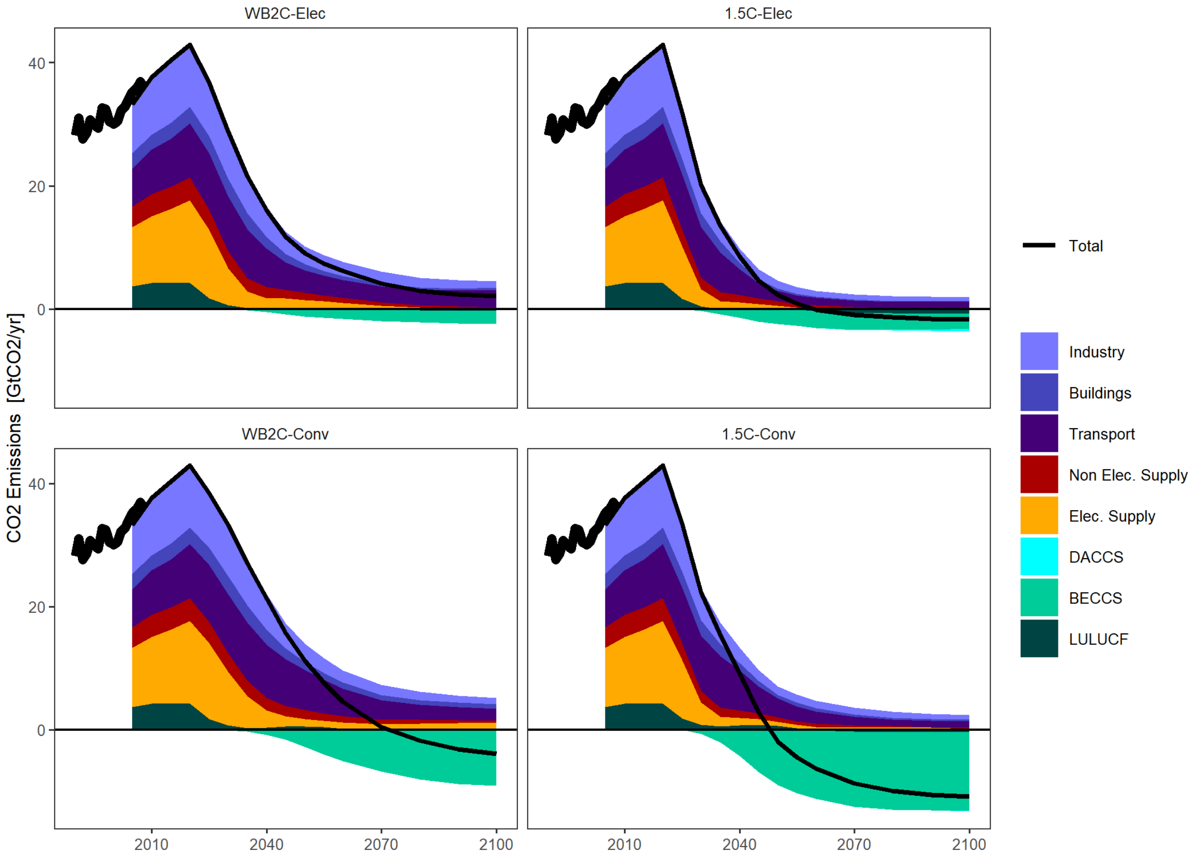
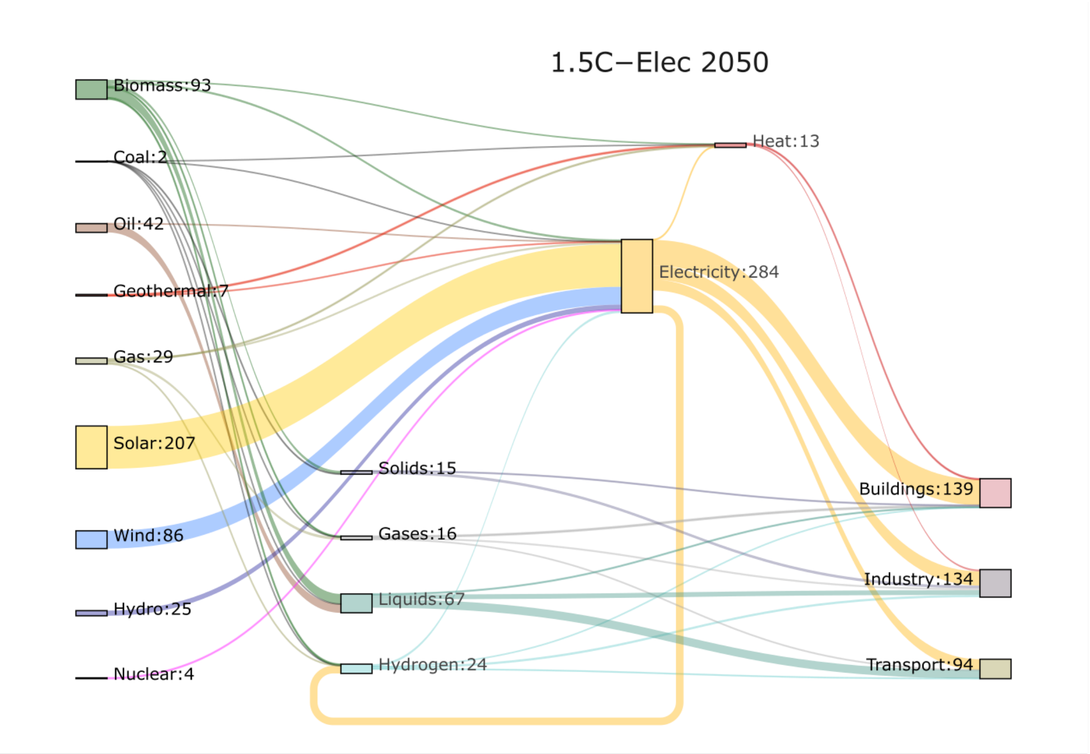
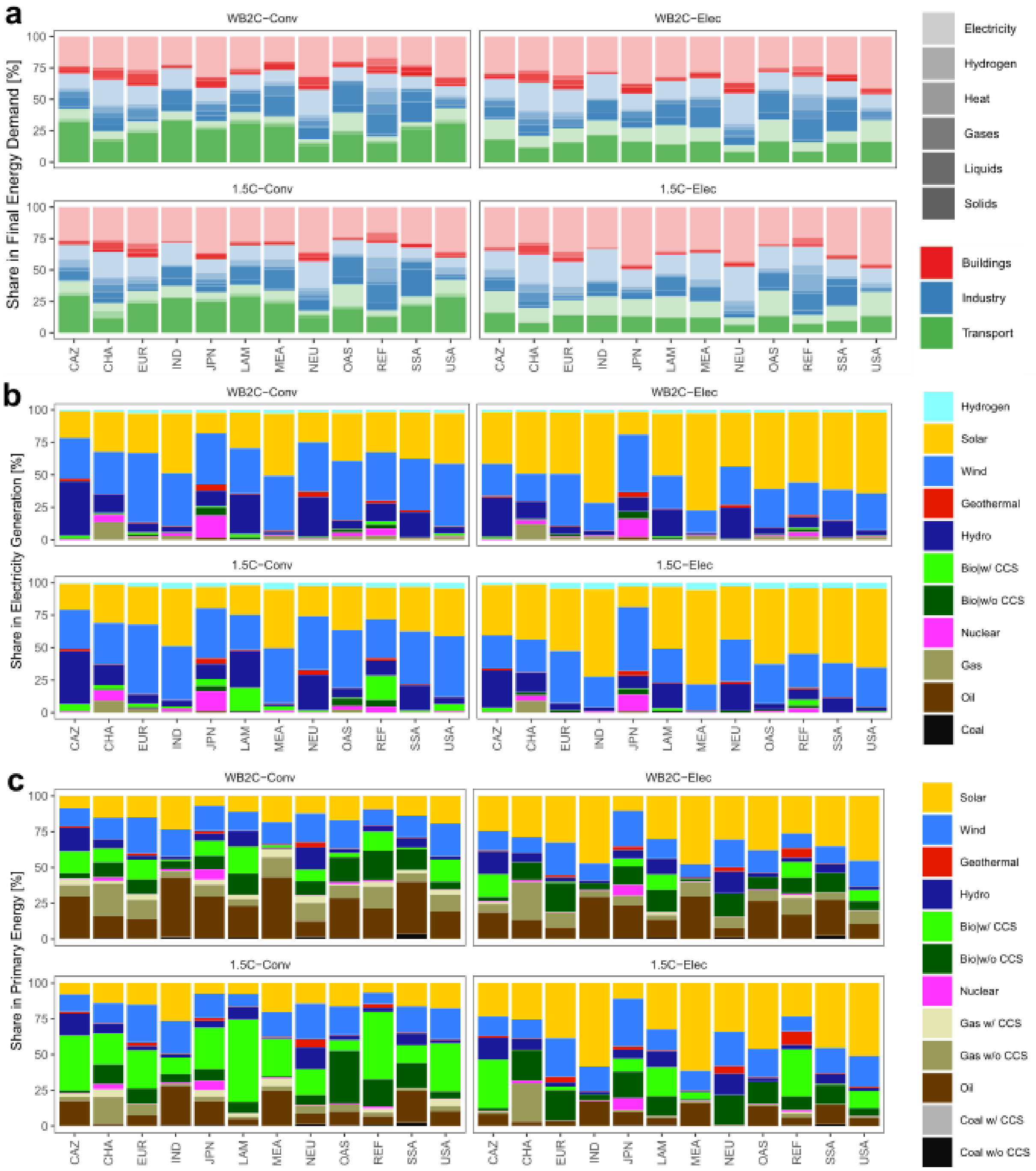


Extended Data Figure 3| Gross residual fossil emissions and carbon dioxide removal. Sectoral residual fossil CO2 (i.e., not accounting for negative emissions from BECCS) emissions from the 785 electricity supply, non-electric supply, transport, buildings and industry sectors (positive emissions). Carbon dioxide removals from BECCS (bioenergy with CCS) and DACCS (direct air carbon capture and storage) are displayed as negative emissions. Emissions from land use, land use change and forestry (LULUCF) are currently net positive but turn net negative in some periods and scenarios.



Extended Data Figure 4| Sankey diagram of energy system flows in 2050 in 1.5C-Elec scenario. Energy flows are given in units of EJ per year and describe secondary energy generation by primary energy input (left to middle), and final energy provision by energy carrier (middle to right).



Extended Date Figure 5| Regional Energy Systems in 2050. Shares of (a) sectors and energy carriers in final demand, (b) technologies in electricity generation, (c) primary energy supply across model regions.