Environmental co-benefits and adverse side-effects of alternative power sector decarbonization strategies

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A rapid and deep decarbonization of power supply worldwide is required to limit global warming to well below 2 °C. Beyond greenhouse gas emissions, the power sector is also responsible for numerous other environmental impacts. Here we combine scenarios from integrated assessment models with a forward-looking life-cycle assessment to explore how alternative technology choices in power sector decarbonization pathways compare in terms of non-climate environmental impacts at the system level. While all decarbonization pathways yield major environmental co-benefits, we find that the scale of co-benefits as well as profiles of adverse side-effects depend strongly on technology choice. Mitigation scenarios focusing on wind and solar power are more effective in reducing human health impacts compared to those with low renewable energy, while inducing a more pronounced shift away from fossil and toward mineral resource depletion. Conversely, non-climate ecosystem damages are highly uncertain but tend to increase, chiefly due to land requirements for bioenergy.
he international community has agreed to limit global warming to well below 2 °C, and to reach net greenhouse gas (GHG) emissions neutrality in the second half of the twenty-first century. Electricity supply is the single most important emissions source sector, accounting for around 40% of global energy-related CO₂ emissions. It also offers the largest low-cost potential for emissions reductions, and thus cost-optimal strategies for keeping global warming to below 2 °C typically feature near-zero electricity sector emissions by mid-century, and rely increasingly on electrification to minimize fossil fuel use in the transport, industry and buildings sectors.

Beyond economic costs and GHG emissions, sound climate policies also have to take into account other sustainability dimensions, such as those laid out in the UN’s Sustainable Development Goals (SDGs) adopted by the United Nations in 2015. The energy sector is the origin of a wide variety of environmental impacts. While much of the public debate focuses on its contribution to global warming via greenhouse gas emissions, energy supply systems also account for substantial shares of other environmental impacts, such as air and water pollution, land occupation, water use, ionizing radiation and nuclear waste, as well as fossil and mineral resource depletion. Energy system futures therefore are particularly relevant for SDGs.

Thus far, there is only very limited system-level research on the benefits and adverse side-effects of future decarbonized power supply in terms of nonclimate environmental impacts. Process-detailed integrated assessment models (IAMs) of the energy-economy-climate system are frequently used to analyze alternative climate change mitigation strategies and their implications, with a focus on greenhouse gas emission reductions. Only recently other specific environmental impacts such as air pollution, land-use for bioenergy, or water demand have been included in IAMs, but so far none of these studies considers the breadth of impacts studied here. Accordingly, a consistent and holistic evaluation of co-benefits of different mitigation pathways is still missing.

By contrast, life-cycle assessment (LCA) as conducted by the industrial ecology community tracks a variety of substance flows and considers a broad set of environmental impacts. But most LCA focuses on current technology and production systems, not accounting for changes in environmental performance of individual technologies (e.g., due to technological learning in the case of photovoltaics), or due to large-scale and structural systemic changes (e.g., a switch towards low-carbon technologies in the context of 2 °C climate stabilization). Some progress towards prospective LCA incorporating future technological changes has been made, using various techniques and approaches for the power sector, and increasingly also end-use technologies. Several studies have performed an ex-post LCA of future national or regional energy scenarios or applied an ex-post LCA to global International Energy Agency scenarios. Other studies have investigated the importance of indirect life-cycle greenhouse gas emissions for optimal decarbonization pathways, but do not consider other environmental impacts.

The novel contribution and main goal of our study is to combine global IAM and LCA approaches, drawing on their specific strengths, to quantify a wide variety of environmental co-benefits and adverse side-effects of a portfolio of alternative power sector decarbonization pathways. In contrast to earlier studies we comprehensively cover all major power technologies, while fully and consistently accounting for system-level interdependencies, future technological change and decarbonization of the supply chain in the context of a global 2 °C climate stabilization effort.

We find that the transition to low-carbon power systems has major co-benefits across a large number of environmental impacts, in particular those related to human health, ecotoxicity and fossil resource use. Land requirements and mineral resource depletion are exacerbated in decarbonization pathways and thus emerge as crucial sustainability trade-offs with climate change mitigation. Our study shows that the scale and profile of co-benefits and adverse side effects depend strongly on technology choice. Co-benefits tend to be greatest for decarbonization strategies focusing on renewable energy technologies.

### Results

#### Alternative power system decarbonization pathways

There are a number of viable technology options for low-carbon electricity supply. Consequently, there is much more flexibility in decarbonizing the power sector than nonelectric energy supply. For instance, some low-carbon electricity pathways rely heavily on nuclear or carbon capture and storage (CCS), while others focus mostly on renewable energy sources. This is reflected in the scenario set considered here: In addition to a Full Technology climate change mitigation scenario (FullTech), we consider two more mitigation scenarios with either a Conventional Technology portfolio (combined share of wind and solar power restricted to 10%—Conv, in line with assumptions in other IAM studies that explored techno-economic impacts of technology constraints), or a New Renewables portfolio (nuclear phase-out, no CCS deployment in the power sector—NewRE) to contrast the implications of opposing mitigation strategies. Moreover, considering a baseline scenario Base without emissions constraint establishes a reference point against which we can evaluate co-benefits and adverse side-effects of power sector decarbonization (Table 1). The resulting electricity generation mixes for the four scenarios and five participating IAMs are shown in Fig. 1 and available in Supplementary Data 1.

#### Impacts on human health

The energy sector poses health risks due to emissions of air, water, and soil pollutants, in addition to those of greenhouse gases. Our analysis framework allows us to contrast these impacts for the four transformation scenarios and to attribute them to specific technologies. It should be noted that the life-cycle assessment approach limits our evaluation to normal operation only, which means that impacts from exceptional events are not considered.

### Table 1 Overview of scenarios considered

| Name                  | Short   | Carbon constraint                                     | Technology availability               |
|-----------------------|---------|-------------------------------------------------------|--------------------------------------|
| Baseline              | Base    | No emissions constraint                               | Full portfolio                       |
| Full technology portfolio | FullTech | Cumulative 2011–2050 power sector emissions limited to 240 GtCO₂ | Full portfolio                       |
| Conventional technology | Conv   | GtCO₂                                                 | Wind and solar power limited to 10% Nuclear phase-out, no CCS in the power sector |
| New renewables        | NewRE   |                                                       |                                      |

We consider three mitigation scenarios consistent with the 2 °C warming limit with different power sector technology portfolios. In addition, a Baseline without emissions constraint serves as a reference point against which co-benefits and adverse side effects of climate policies can be evaluated.
(e.g. dam failures, mining accidents, pipeline explosions, or nuclear meltdowns) are excluded from this analysis.

The power sector is one of the major sources of air pollutant emissions, and air pollution is a major threat to human health\(^3\). In 2010, the power sector accounted for around 40% for global SO\(_2\) emissions, and 20% of NO\(_x\). These substances are important precursors for particulate matter formation (PM-10) (Fig. 2a). NO\(_x\), along with CH\(_4\) and other volatile organic compounds (NMVOCs), also enhance photochemical oxidant formation, i.e., tropospheric ozone (Fig. 2b). In particular PM-10 but also tropospheric ozone are important health threats\(^3\). In line with previous studies\(^8,17\), we here find that air pollutant emissions and concentrations stabilize or decrease slightly even with a massive upscaling of fossil-based power production in absence of climate policies (Fig. 2a). This is largely due to increasing regulation and end-of-pipe measures to control pollution\(^8,40\) and follows the historical trend in industrialized countries\(^3\). The power sector’s contribution to PM-10 and ozone originates almost exclusively from the combustion of fossil fuels and bioenergy (Fig. 2a, b). Our analysis also accounts for upstream emissions due to indirect energy demands for the construction of energy conversion technologies, fuel production and handling. However, we find that upstream fossil fuel use\(^25\) and indirect air pollution associated with noncombustion power technologies are rather small compared to direct emissions (see Supplementary Fig. 1).

Climate change mitigation lowers air pollution drastically and more so in the NewRE than in Conv scenarios. On average across models, the decline of fossil-based power in NewRE climate policy results in reductions of 87% and 83% of PM-10 and ozone precursors, respectively, relative to the baseline case. Air pollution impacts in the Conv case are around double of those in the NewRE case, largely due to greater remaining direct NO\(_x\) emissions as well as higher indirect air pollution from upstream energy requirements for the extraction and handling of fossil fuels. This is despite strong co-control of sulfur in CCS plants (Fig. 3, Supplementary Fig. 2 and ref. \(^41\)).

All energy technologies cause human toxicity impacts due to chemical toxicant emissions in their supply chains, albeit at different scales (Fig. 2c). They are particularly high for coal (leaching of toxicants from mine dumps), bioenergy (agrochemicals use in agriculture), and still significant for gas (emissions during natural gas extraction), nuclear (tailings from uranium mining and milling) and photovoltaics (emissions from copper processing and silicon refinement). Overall, a pattern similar to air pollution impacts emerges: human toxicity is strongly reduced under climate policies, and around 60% lower in NewRE compared to Conv.
Another relevant impact from the power sector stems from the ionizing radiation emitted by radioactive substances (Fig. 2d). Ionizing radiation is almost exclusively caused by nuclear power, and dominated by releases from mining and milling during the production of nuclear fuels. Per-unit impacts for all other technologies, including coal power, are more than two orders of magnitude smaller (see Supplementary Fig. 2) and largely due to upstream nuclear power use. Importantly, LCA inventories and assessment methods do not account for the risk of radiation exposure nuclear accidents\textsuperscript{42}. However, analysis by Hirschberg et al.\textsuperscript{43} and others\textsuperscript{44,45} suggest first that, in terms of lost life years, fatalities from accidents tend to be considerably smaller than health impacts from regular operation, and second that fatalities from nuclear accidents tend to be lower than those from fossil-based or hydropower.

Fig. 2 Environmental impacts affecting human health. Globally aggregate environmental impacts from a particulate matter formation, b photochemical oxidant formation, c human toxicity, and d ionizing radiation, in 2010 and 2050 under different power sector transformation scenarios. Stacked bars indicate mean across all combinations for LCA technology variants and IAM scenario realizations. Boxplots indicate median and interquartile ranges across technology variants and participating integrated assessment models, whiskers 10th–90th percentile ranges. Ranges do not reflect uncertainty in environmental impact characterization. Base Grid refers to generic grid requirements determined by total electricity demand, while VRE grid refers to additional grid requirements for coping with the variability of renewable electricity supply from wind and solar power.

In the absence of climate policies, models project an increase of around 50% nuclear power use by 2050, resulting in a corresponding rise in related radiation impacts. Climate change mitigation could result in a further expansion of nuclear power and corresponding radiation impacts by a factor of 3–7 in the FullTech scenarios relative to 2010, or even 5–8 if the use of wind and solar power is limited (Conv scenarios). In the NewRE scenarios, by contrast, ionizing radiation impacts are limited to the extent that pre-existing nuclear power plants are phased out of power supply. The analysis of endpoint impacts indicates that ionizing radiation contributes less to human health impacts than particulate matter, ozone, or other toxic pollution (combined assessment section).

Ecosystem damage. The power sector also threatens the health of ecosystems. Relevant impact channels include land occupation and transformation, as well as pollutant release resulting in terrestrial acidification, eutrophication and ecotoxicity impacts.

Land-use for agricultural and other human activities is a crucial driver of global biodiversity loss and degradation of many ecosystem services\textsuperscript{46}. In 2010, the land footprint attributable to power supply compared to around 12% of total built-up area\textsuperscript{47}. The ReCiPe LCIA differentiates between land occupation of areas already transformed from its natural state, and natural land transformation, e.g. from forests to croplands. Natural land transformation accounts for the quality of the land being transformed, putting particular emphasis on reduction of biodiversity-rich forest areas. In all scenarios considered, both land occupation (Fig. 4a) and natural land transformation (Fig. 4b) for power supply will increase in the future relative to
current level. In Base, the power sector’s land-use increases due to an increase of the power system’s scale and is largely attributable to coal (both area occupied by open-cast coal mines, and land-use associated with timber used for the support of underground mines), biomass and hydropower (land-use for reservoirs). We find that climate policy tends to increase power-system related pressure on land, largely because of increasing biomass use. On a per-MWh basis, electricity from biomass with CCS is more than 20 times more land-intensive than hydropower, coal with CCS, or CSP, and exceeds wind and PV by around two orders of magnitude (Fig. 3). Due to the deforestation induced by biomass expansion, bioenergy figures even more prominently in natural land transformation impacts. Overall, bioenergy-induced land-use impacts tend to be greatest in the Conv scenarios, as negative emissions from BECCS are required to compensate for residual CO₂ from imperfect carbon capture in fossil CCS plants. Importantly, however, we find very high uncertainty—i.e., technology, policy and management dependence—in the ecosystem impacts form land-use, with the variability induced by management practices and IAM model uncertainty exceeding the differences across scenarios (Supplementary Fig. 3). In comparing fossil to nonfossil power generation, it is also important to emphasize that our analysis does not account for habitat losses caused by coastal flooding. Due to higher climate change-induced sea level rise, coastal flooding will be more severe in the Base scenario than in the climate change mitigation scenarios.

Another important factor for the land footprint of electricity supply systems is the grid infrastructure for transmission and distribution, which accounts for around one third of the total. As an expansion of grid interconnectors is an important option for coping with the variability of wind and solar power supply, we here account explicitly for the dependence of transmission grid requirements on the generation share of wind and solar (see Methods). However, we find that the land occupation attributable to additional grid requirements for wind and solar integration is small compared to the land footprint from the general electricity grid.

Further ecosystem damage is inflicted from the release of various chemical substances. Atmospheric sulfur and nitrogen oxides from combustion result in terrestrial acidification. In line with the reduction of health impacts from air pollution, terrestrial acidification is projected to decline slightly under the baseline scenario, and to fall to less than a fifth of current levels by 2050 under 2 °C-consistent stabilization (Fig. 4c). Similar to toxicants harmful to humans, all technologies feature life-cycle ecotoxicity impacts (Fig. 4d). However, on a per-MWh basis, these are greatest for fossil technologies (emissions during extraction), substantial for bioenergy (agrochemicals use for crops), and much smaller for wind and solar (Supplementary Fig. 2). As a consequence, ecotoxicity impacts in the NewRE decarbonization scenarios are around 30% lower than those in FullTech. As the Conv scenarios rely more heavily on natural gas with CCS, ecotoxicity impacts are 25% greater than in FullTech, and on average around double those estimated for 2010.

Another relevant channel for ecosystem impacts are marine and freshwater eutrophication (Fig. 4e, f). The leaching of phosphate from coal production is the dominant contributor to freshwater eutrophication impacts, as ReCiPe assumes phosphate to be the primary limiting nutrient for freshwater ecosystems. In contrast to freshwater, nitrites induce a higher eutrophication response for marine ecosystems. Emissions of nitrogen oxides from combustions as well as direct nitrate releases from fertilizers for bioenergy cultivation therefore contribute to marine eutrophication. For both freshwater and marine eutrophication, the strong reduction of fossil fuel use results in substantial decreases in mitigation scenarios compared to Base. These co-benefits are greatest for the NewRE scenarios.

Not only the contamination of water with chemical substances, but also its withdrawal from river systems is an important environmental stressor. Electricity supply systems account for approximately 14% of global human water withdrawal. Most thermal power plants use water for cooling, while hydroelectric plants affect waterways through dams and water losses to evaporation and seeping. As discussed in earlier literature, future projections of water withdrawals are highly uncertain as they depend on the degree to which utilities adapt to water scarcity, for instance by installing dry cooling technologies in thermal power plants. Besides cooling water, water losses from hydropower and withdrawals for biomass irrigation are projected to increase substantially in the future. Across decarbonization scenarios, water withdrawal is highest in the Conv scenarios due to the large share of nuclear power, which is particularly cooling-water-intensive. The NewRE scenarios, by contrast,
have very little thermoelectric capacities, and thus feature distinctly lower water withdrawals than the Conv and FullTech scenarios.

**Exhaustible geological resources.** Beyond damages to human health and ecosystems, the energy sector also contributes strongly to the depletion of exhaustible resources, thus reducing natural capital and options for future generations. It is important to keep in mind that the health and ecosystem damage associated with resource extraction are already accounted for in the other impact indicators, such as ecotoxicity or human toxicity.

In absence of climate policies, fossil depletion is projected to roughly double by mid-century relative to 2010 levels, as supply-side efficiency improvements and the contributions of renewables and nuclear are insufficient to offset strongly increasing electricity demand (Fig. 5a). Climate policy does not necessarily reduce fossil depletion, as gas with CCS becomes increasingly important and replaces coal. In the Conv and FullTech cases, around half the models project 2050 fossil use for power supply to exceed 2010 levels. In NewRE case, by contrast, the models project on average an around 75% reduction of fossil depletion relative to 2010 levels.
fluctuations from wind and solar electricity accounts for most of the remaining fossils in these NewRE scenarios. Indirect fossil energy requirements for power supply, e.g., manufacturing of solar panels, are fully accounted for in our analysis but found to be relatively small even in the NewRE scenario.

In the FullTech and Conv scenarios, the continued use of fossils can only be reconciled with the tight emissions constraints via carbon capture and storage (CCS). This gives rise to geological CO2 storage as a new exhaustible resource depleted by the energy sector. Our results indicate that the power sector would account for around 11 [4–16] GtCO2/yr storage requirements in FullTech, and 15 [10–21] GtCO2 in the Conv scenarios (Fig. 5c) by 2050, which increases further in the majority of model simulations thereafter (Supplementary Fig. 4). The power sector competes with other potentially important CCS use cases, such as biomass with CCS for nonelectric fuels, CCS for industry, or direct air capture. While currently available estimates suggest a total geological technical potential for CO2 storage of at least ~2000 GtCO252, economically and societally acceptable CO2 storage potentials are likely to be much more limited.

Power supply also accounts for a substantial share of mineral resource depletion, mostly for the construction of power generators. In 2010, around 5% of global copper, 2.5% of aluminum, and 3% of iron went into the electricity supply sector53. Mineral resource depletion accounts for the aggregate demands from these bulk metal demands along with some 20 other important mineral resources. It should be noted that concerns about mineral resource depletion involve a large number of minerals, not all of which are covered by life-cycle impact assessment methods. For example, the indicator used here does not include neodymium or dysprosium (used in certain wind turbines54), or indium or tellurium (used in certain photovoltaic cells)54. In all scenarios, nonfuel mineral depletion increases relative to current levels. In contrast to all other indicators we find that all climate policy scenarios feature higher mineral resource requirements, and that in the NewRE scenarios 2050 mineral resource depletion is around twice as high as in FullTech, and around four times higher than in the baseline (Fig. 5b). This is explained, first, by the higher per-unit metal requirements for renewable technologies, particularly solar PV; second, the fact that wind and solar technologies require substantial material upfront investments before operation (which here are attributed to the year of construction); and finally, to a lesser extent, the additional metal resources required for the build-up of additional grid and storage infrastructure to accommodate the variability of wind and solar power supply.

Fig. 5 Resource impacts. Globally aggregate resource impacts from a fossil depletion, b mineral resource depletion, and c geological CO2 storage requirements, for 2010 and 2050 under different power sector transformation scenarios. Stacked bars indicate mean across all combinations for LCA studies and IAM scenario realizations. Boxplots indicate median and interquartile ranges across technology variants and participating integrated assessment models, whiskers 10th–90th percentile ranges. Ranges do not reflect uncertainty in environmental impact characterization.
Combined assessment. The comparison of differences across scenarios demonstrates that electricity decarbonization has substantial nonclimate co-benefits for most environmental impacts at the midpoint level of the cause-effect chain (Fig. 6a), as well as the human health and resource depletion impacts at the endpoint level (Fig. 6b–d). However, some environmental pressures induced by power supply emerge as crucial concerns, as they are likely to increase in the future and might be exacerbated by the low-carbon transformation: first, land requirements; second, mineral resource depletion; and third, impacts related to the use of radioactive materials, not only ionizing radiation as considered here, but also the risk of nuclear accidents and the production of nuclear waste.

We further find that different decarbonization strategies result in distinctly different profiles of risks and co-benefits. Wind and solar-based decarbonization (NewRE scenario) consistently achieves highest reductions in health-related environmental impacts (Fig. 6b). Fossil technologies—especially coal—dominate aggregate health impacts by far (see Supplementary Fig. 5); thus, their faster and deeper phase-out in the NewRE scenarios yields greatest benefits, with around 60% lower aggregate mortality compared to Conv, and an around 50% decrease relative to FullTech in 2050. The most prominent contributors to health impacts are air pollution and human toxicity.

NewRE decarbonization also minimizes pollution-related ecosystem impacts compared to Conv and FullTech scenarios. Aggregate ecosystem damage, as derived from the corresponding ReCiPe endpoint characterization factors, are dominated by land occupation and natural land transformation. These land-use related impacts are highly uncertain and of comparable magnitude across the different decarbonization scenarios: While NewRE scenarios are characterized by greater land-requirements for wind and solar power as well as grid expansion, the higher bioenergy deployment in the Conv scenarios induces greater natural land transformation (Fig. 6c and Supplementary Fig. 5).

We also find that decarbonization will fundamentally change the resource requirements of the power sector, away from fossil fuel inputs and towards mineral resources (FullTech and NewRE)
and geological storage space for CO₂ (FullTech and Conv). For the NewRE scenarios in 2050, fossil depletion decreases by 90%, while bulk material requirements increase four-fold compared to baseline levels. In addition, certain wind power and photovoltaics technologies also rely on specialty minerals, such as dysprosium or indium, which are not addressed in the resource depletion assessment method employed here, but are subject to geopolitical supply risks. The low-carbon transformation, especially if it relies heavily on wind and solar technologies, can be expected to have profound implications for the geopolitical landscape, pointing to the need for flanking the global clean energy effort with an integrated critical materials strategy.

Fossil fuels by far dominate resource surplus costs, the aggregate ReCiPe endpoint indicator for resource depletion. This result suggests that the benefit to society stemming from reduced fossil requirements in NewRE outweigh the burden due to additional mineral resource depletion. In addition, it should be kept in mind that much of the 2050 resource requirements for wind and solar installations can be attributed to upfront investment for electricity produced later, and that mineral resources are amenable to recycling, while fossil resources are not.

In terms of technologies, fossil fuels are the major drivers of health impacts and also dominate resource surplus costs; thus, their reduction in the context of climate policies yields substantial benefits. Bioenergy emerges as the greatest driver of ecosystem damage, chiefly due to land occupation and induced loss of natural lands. On the other hand, numerous studies have demonstrated the importance of bioenergy for the 1.5 and 2°C targets, both due to its versatility in substituting fossil fuels and the possibility of generating negative emissions. This underlines the need for an integrated global land management to navigate the tradeoff between climate change mitigation and conservation.

**Discussion**

The world is currently witnessing a dynamic and robust growth of wind and solar power, which is also expected to become the most important contributor towards near-term CO₂ reduction efforts worldwide. Our results suggest that further relying predominantly on these new renewables in the transition towards a near-zero emissions power system also reduces most nonclimate environmental impacts on the system level compared to strategies that limit the contribution of wind and solar power largely in favor of greater CCS deployment.

It is important to bear in mind that our forward-looking global analysis with wide system boundaries, despite the methodological advancements brought by integrating integrated assessment models and prospective life-cycle assessments, is subject to significant limitations and uncertainties. For example, the linearized approach of life-cycle impact assessment cannot account for scale-dependent variations in per-unit impacts, e.g., to threshold or saturation effects, or interaction among different environmental impacts. Human toxicity and ecosystem impacts are subject to spatial variability. Changes in population and age structure matter for health damages, ecosystem damage will depend on future land-use patterns, and the economic consequences of resource depletion on competing resource uses. Our study accounts for dynamic changes in technical systems (e.g., increased material efficiency of PV cells, or reduction of air pollution due to end-of-pipe measures), but lacks a dynamic description of crucial nonclimate environmental mechanisms, mostly due to a lack of knowledge or demonstrated importance of relevant developments. While our analysis accounts for uncertainties in energy technology deployment as well as innovation in individual technologies, we were not able to account for uncertainties in the characterization factors translating stressor flows to environmental impacts (see Methods).

We deliberately focused our analysis on the year 2050, since by mid-century the decarbonization of power systems is largely completed and technology developments get increasingly uncertain with longer time horizons. Nonetheless, it is important to note that environmental impacts of a decarbonized power system might continue to evolve thereafter, depending on size and composition of power supply. For instance, increasing contributions of biomass to electricity generation, as projected in many IAM scenarios, will exacerbate ecosystem damages.

**Methods**

**Overview of modeling approach.** Our study incorporates a number of innovative methodological features. By using five structurally different IAMs (GCAM, IMAGE, MESSAGE-GLOBIOM, POLES, REMIND) we are able to capture diversity in system transformations for given climate and technology policy assumptions. The IAMs represent several environmental impact mechanisms directly and by source, in particular air pollution (resulting in particulate matter formation, oxidant formation and terrestrial acidification), water use for cooling and hydropower as well as fossil resource depletion. Land requirements, fertilizer use, irrigation water and land-use change emissions from bioenergy production have been estimated from the MagPIE land-use management model, allowing to account for indirect effects of bioenergy (such as induced deforestation) in a dynamic setting. In addition, we estimate requirements for power transmission grids and electricity storage using a regression from the detailed power system models REMIX and DIMES. We combine IAM-based technology deployment pathways with per-unit environmental impact and indirect energy requirements derived from the multiregional LCA model THEMIS. This allows accounting for future technological change, e.g. in terms of improved material efficiency, changes of energy mixes, biomass power systems, or material demands for solar PV (see Methods). We further use the ReCiPe life-cycle impact assessment (LCIA) methodology, which allows us on the one hand to expand the assessment to include human toxicity, ionizing radiation, land occupation, terrestrial, freshwater and marine ecotoxicity, marine and freshwater eutrophication, as well as mineral resource depletion, and on the other hand to not only consider direct, but also indirect environmental impacts associated with manufacturing or other supply chain activities. In an additional step, in line with the established ReCiPe LCIA, we aggregate the above-mentioned impacts (midpoints along the cause-effect chain) to the three endpoint categories human health, ecosystem damage and resource depletion. Importantly, the endpoint impacts are subject to much greater uncertainty than midpoints. We therefore use endpoint results mainly as an indicative guide to the relative severity of the various impacts, and for relative comparison of different decarbonization pathways. Importantly, we note that the ranges provided in the figures and quantitative results only reflect uncertainties in technology choice and technological development of individual technologies, but not the uncertainty from environmental impact characterization, which is unavailable in the ReCiPe methodology. A detailed description of the approach is presented in Methods.

**IAM scenarios and technology deployment.** To characterize alternative decarbonization strategies in terms of their environmental impact, we combine IAM scenarios with LCA data for specific power sector technologies. To account for the uncertainties about future developments, these scenarios were run by the five integrated assessment models GCAM, IMAGE, MESSAGE-GLOBIOM, POLES and REMIND. These five IAMs are well-established modeling systems and have participated in numerous prior multi-model studies of long-term and global energy transformation pathways (e.g., ref. 9). They are characterized by a broad coverage...
of power sector technologies and process detail in the energy system. All five models represent air pollution and water requirements by source. A more detailed description of the five IAM models can be found in the Supplementary Information. The scenario set comprises one baseline scenario without any climate policies and four alternative climate policy scenarios with different policy choice (Table 1). All climate policy scenarios limit the cumulated 2011–2050 CO2 emissions from the power sector to 2.4 GtCO2, resulting in an at least 80% reduction of emissions by 2050. CO2 emissions are kept consistent with characterization factors used in this study. We consider three decarbonization scenarios with different assumptions on technology availability. In the default FullTech scenario, no technology constraints are applied, such that the cost-minimizing mix of low-carbon alternatives is chosen. To contrast our analysis with a middle-of-the-road approach whereby impacts are calculated for a 100-year time horizon, depending on the perspective the practitioner wants to take, we also report results for the short-term and long-term storage requirements, calculated based on the values in ref. 64: For eight world regions, storage deployment is optimized by the hourly dispatch and investment model DIME for a wide range of wind and solar shares. From these results, a polynomial fit is derived. In the current study, we apply this equation to the wind and solar energy deployed by the five IAMs. By default, storage is assumed to be deployed by default as lithium-ion batteries, while compressed-air and pumped-hydro storage systems are considered as sensitivity cases. Long-distance transmission grid expansion is estimated based on a generalized equation derived from scenarios produced with the hourly dispatch and investment model REMIX with endogenous transmission grid expansion15, from which the additional grid investment per unit of wind and solar energy is calculated as a function of the share of wind and solar in total power supply.

Life-cycle assessment modeling. Life-cycle impact assessment (LCIA) methods encompass models and characterization factors that aim at converting a list of environmental interventions into indicators representing environmental impact categories. The variety of impact assessment models available for LCA is wide, and the uncertainty attached with each set of characterization factors may also range across different value choices available from ReCiPe, we chose the hierarchical perspective with opposite visions of the future role of variable renewable electricity generation, we considered two technology variants Conv and NewRE. In the Conv scenario, the share of variable renewable electricity supply is limited to 10%, resulting in an energy system largely based on conventional thermal power plants, with a strong emphasis on nuclear and CCS. In the NewRE scenario, by contrast, CCS is assumed to be unavailable and nuclear power is phased out, resulting in a scenario with large shares of electricity supply from new renewables, i.e., wind, and solar technologies. The IAM scenarios are available as Supplementary Data 1. Similar sensitivity cases were considered in earlier IAM studies assessing energy system and cost implications of technology choice.5,26

All IAMs used here represent the continued evolution of energy systems and technological progress in energy technologies over time, either by applying exogenous cost reductions based on bottom-up estimations (GCAM and MESSAGE models), or through endogenous modeling of learning-by-doing (REMIIND, IMAGE, POLES models). Regional differences in renewable energy deployment are captured by regional representation of availability of competing technologies8, and temporal matching between RE supply and demand4,6,8. The IAMs do not account for the impact of climate change on renewable energy resources. Our analysis also accounts explicitly for the deployment of storage and the expansion of long-distance transmission grids to sustain a high share of variable power supply at high shares of wind and solar. We estimate short-term storage requirements, calculated based on the values in ref. 64. For eight world regions, storage deployment is optimized by the hourly dispatch and investment model DIME for a wide range of wind and solar shares. From these results, a polynomial fit is derived. In the current study, we apply this equation to the wind and solar energy deployed by the five IAMs. By default, storage is assumed to be deployed by default as lithium-ion batteries, while compressed-air and pumped-hydro storage systems are considered as sensitivity cases. Long-distance transmission grid expansion is estimated based on a generalized equation derived from scenarios produced with the hourly dispatch and investment model REMIX with endogenous transmission grid expansion15, from which the additional grid investment per unit of wind and solar energy is calculated as a function of the share of wind and solar in total power supply.

Integration of IAM scenarios and LCA. Table 2 provides an overview of the environmental impacts considered at the midpoint of the cause-effect chain and briefly describes of the approaches used to estimate impact indicator results. A central strength of our study is the integration of energy flows and environmental impacts represented directly by IAMs and prospective LCA coefficients derived from the THEMIS model25. Following recommendations of ref. 28, we combine LCA energy coefficients broken down into life-cycle phases (i.e., construction, operation and end-of-life phases for each power-generation technology) and industrial processes, as well as for different fuel types and energy carriers, with the results of integrated IAM and LCA models. The integration of the energy flows and environmental impacts used for this method were derived from the THEMIS model25. Following recommendations of ref. 28, we combine LCA energy coefficients broken down into life-cycle phases (i.e., construction, operation and end-of-life phases for each power-generation technology) and industrial processes, as well as for different fuel types and energy carriers, with the results of integrated IAM and LCA models. The integration of the energy flows and environmental impacts used for this method were derived from the THEMIS model25. Following recommendations of ref. 28, we combine LCA energy coefficients broken down into life-cycle phases (i.e., construction, operation and end-of-life phases for each power-generation technology) and industrial processes, as well as for different fuel types and energy carriers, with the results of integrated IAM and LCA models.
Table 2 Overview of methodologies for specific environmental impacts

| Impact                                                                 | Methodology                                                                 |
|-----------------------------------------------------------------------|-----------------------------------------------------------------------------|
| Human toxicity, freshwater ecotoxicity, marine ecotoxicity, terrestrial ecotoxicity, freshwater eutrophication, marine eutrophication, ionizing radiation, mineral resource depletion | Life-cycle impact coefficients derived from THEMIS for individual life-cycle stages of each power-generation option are combined with activity data (i.e., new installed capacities, power generation) from the IAM scenarios. For the assessment of bioenergy, region- and scenario-specific yield ratios, nitrogen and phosphorus fertilizer requirements, and irrigation requirements dynamically derived from the MAgPIE model are incorporated into THEMIS. Effects of individual pollution and natural resource types are aggregated using ReCiPe characterization factors.  
Land occupation and natural land transformation                          | Air pollution emissions in IAM scenarios are based on technology-specific emission factors from the GAINS model (ref. 40,9) combined with life-cycle coefficients of indirect energy requirements derived from THEMIS for individual life-cycle stages of each power-generation option. Air pollution emissions of SO₂, NOₓ, CH₄, BC, OC and NMVOC are represented by source and energy technology in all IAMs. Effects of direct and indirect emissions of all pollution types are aggregated using characterization factors from ReCiPe.  
Particulate matter formation, photochemical oxidant formation, and terrestrial acidification | Fossil resource use and CO₂ storage requirements are represented explicitly in all IAMs. Also upstream fossil resource and CO₂ storage requirements are derived via combination with life-cycle coefficients of indirect energy requirements derived from THEMIS.  
Water withdrawal                                                        | Water withdrawals for power plants (mostly cooling) are represented by source in all participating IAMs. In addition, we account for irrigation of bioenergy as derived from the MAgPIE model.  
Fossil resource depletion and geological CO₂ storage requirements      |  

Our analysis focuses on nonclimate environmental impacts of alternative climate change mitigation strategies, and therefore deliberately left out the climate change midpoint indicator.

The LCA coefficients are differentiated by two generic scenarios, indicating either a continuation of current trends (Baseline), or strong improvements in material and energy intensity of industrial processes (BLUE Map). These are matched to the IAM scenarios and regions as follows. The BLUE Map LCA coefficients are used for all IAM scenarios with stringent climate protection policies, whereas the Baseline LCA coefficients are used for IAM scenarios with no or insufficient mitigation efforts. IAM regions are matched to the THEMIS region with the best regional fit. The power systems’ environmental impacts were calculated for each IAM model region, scenario and technology by multiplying the capacity additions and operation as derived from the IAMs with LCA impact coefficients derived with THEMIS and then aggregated to the global totals shown in the analysis of the paper.

Our combined IAM and LCA analysis captures the different timing of infrastructure and operational effects, allowing us to apply LCA impact data (e.g., emission factors) to the appropriate years when activities occur. It also allows us to capture the need to make upfront infrastructure investments for electricity generation later, the relevance of which has been noted by others6,69. Further, by decomposing LCA coefficients into four energy carriers (solid, liquid and gaseous fuels, and electricity) and assigning them to IAM scenario-specific emission intensities (for fuels and electricity), we are able to consistently account impacts related to indirect energy requirements66.

Special attention is needed for environmental impacts related to land-use, since for many technologies, the definition of land occupation is highly uncertain or difficult to define, indirect effects (e.g., relocation of nonenergy croplands in response to bioenergy cultivation) play an important role, and while they are a dominant contributor to ecosystem damage, these damages are highly location-specific and therefore very uncertain in the global aggregate.

For biomass, land-use impacts depend critically on the assumptions regarding land management practices and policies. For purpose grown bioenergy, we therefore analyze nine cases with different assumptions on land management and policies (types of biomass feedstocks, biomass irradiation, regulation of land-use CO₂ emissions). Most importantly, we assume different stringency levels for the regulation of GHG emissions from the land-use sector, distinguishing three cases: No emissions regulation, weak regulation of agricultural and land-use change emissions, emulated using a carbon price of 5 $/tCO₂ in 2020 increasing at 5% p.a., and strong regulation of agricultural and land-use change emissions, emulated using a carbon price of 30 $/tCO₂ in 2020 increasing at 5% p.a., a level comparable to the CO₂ price in the energy sector required for the 2 °C limit. These sensitivity cases give rise to a substantial range in environmental impacts of bioenergy, such as land occupation and land transformation (see Supplementary Fig. 3). In particular, strong carbon regulation dis-incentivizes natural land transformation, and instead results in greater agricultural intensification, while weak carbon regulation exacerbates land-use impacts. The resulting per-unit bioenergy coefficients are documented in Supplementary Data 3.

The results on land occupation for nonbioenergy technologies are also highly uncertain. For instance, the land occupation of PV depends crucially on the share of ground-mounted vs. buildings-integrated solar, which we here assume to reach 75% by 2050. With exceptions60, onshore wind power LCA studies typically account for the direct footprint of the wind turbine, machine houses and access roads, but not the space between wind turbines in a wind park, which can remain natural habitat or be exploitable for other uses, e.g. agriculture or forestry6,69. The total land occupied by an onshore wind farm is around 50−200 m²a/MWh, much higher than the direct wind infrastructure space requirement66.

The aggregation of midpoint environmental impacts to the three endpoint impacts human health, ecosystem damage and resource depletion presented in Fig. 6 is also based on the ReCiPe methodology61. No midpoint-to-endpoint characterization is available in ReCiPe 2008 for marine eutrophication and water withdrawals (owing to unavailability of adequate assessment methods) and geological CO₂ storage (not considered in ReCiPe).

Resulting technology, scenario and IAM-specific environmental impacts are documented in Supplementary Data 4.

Data availability

The datasets generated and analyzed during this study are available as supplementary data.

Code availability

The code for integrating IAM scenario results with LCA environmental impact coefficients is available at Zenodo repository https://doi.org/10.5281/zenodo.3529760. The code also includes the analysis routines for creating the figures.
57. Schneider, L. et al. The economic resource scarcity potential (ESP) for evaluating resource use based on life cycle assessment. Int. J. Life Cycle Assess. 13, 601–610 (2008).
58. Beck, B. K. & Graedel, T. E. Challenges in metal recycling. Science 337, 690–695 (2012).
59. Rose, S. K. et al. Bioenergy in energy transformation and climate management. Clim. Change 123, 477–493 (2013).
60. Viatici, Z. et al. Enhancing global climate policy ambition towards a 1.5 °C stabilization: a short-term multi-model assessment. Environ. Res. Lett. 13, 044039 (2018).
61. Bauer, N. et al. Global energy sector emission reductions and bioenergy use: overview of the bioenergy demand phase of the EMF-33 model comparison. Clim. Change. https://doi.org/10.1007/s10584-018-2226-y (2018).
62. Huijbregts, M. A. J. et al. ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. Int. J. Life Cycle Assess. 22, 138–147 (2017).
63. Lotze-Campen, H. et al. Global food demand, productivity growth, and the scarcity of land and water resources: a spatially explicit mathematical programming approach. Agric. Econ. 39, 325–338 (2008).
64. Ueckerdt, F. et al. Decarbonizing global power supply under region-specific consideration of challenges and options of integrating variable renewables in the REMIND model. Energy Econ. 64, 665–684 (2017).
65. Luderer, G. et al. Deep Decarbonization towards 1.5 °C – 2 °C Stabilization: Policy Findings from the ADVANCE Project (2016). http://www.fp7-advance.eu/sites/default/files/documents/WP7/ADVANCE-Synthesis-Report.pdf.
66. Pietzcker, R. C. et al. System integration of wind and solar power in integrated assessment models: a cross-model evaluation of new approaches. Energy Econ. 64, 583–599 (2017).
67. Hauschild, M. Z. & Huijbregts, M. A. J. Introducing life cycle impact assessment in Life Cycle Impact Assessment (eds Hauschild, M. Z. & Huijbregts, M. A. J.) 1–16 (Springer, Netherlands, 2015). https://doi.org/10.1007/978-94-017-9744-3_1.
68. Huijbregts, M. A. J. Application of uncertainty and variability in LCA. Int. J. LCA 23, 273 (1998).
69. Bach, V., Möller, F., Finogenova, N., Emara, Y. & Finkbeiner, M. Characterization model to assess ocean acidification within life cycle assessment. Int. J. Life Cycle Assess. 21, 1463–1472 (2016).
70. Woods, J. S., Veltman, K., Huijbregts, M. A. J., Verones, F. & Hertwich, E. G. Towards a meaningful assessment of marine ecological impacts in life cycle assessment (LCA). Environ. Int. 89–90, 48–61 (2016).
71. Verones, F. et al. Harmonizing the assessment of biodiversity effects from land and water use within LCA. Environ. Sci. Technol. 49, 3584–3592 (2015).
72. Ueckerdt, F., Hellweg, S., Pirot, S. & Huijbregts, M. A. J. Impacts of river water consumption on aquatic biodiversity in life cycle assessment—a proposed method, and a case study for Europe. Environ. Sci. Technol. 48, 3236–3244 (2014).
73. Chaudhary, A., Verones, F., De Baan, L. & Hellweg, S. Quantifying land use impacts on biodiversity: combining species–area models and vulnerability indicators. Environ. Sci. Technol. 49, 9987–9995 (2015).
74. Douziech, M. et al. Confronting variability with uncertainty in the ecotoxicological impact assessment of down-the-drain products. Environ. Int. 126, 37–45 (2019).
75. Vieira, M. D. M., Ponsioen, T. C., Goedkoop, M. J. & Huijbregts, M. A. J. Surplus ore potential as a scarcity indicator for resource extraction. J. Ind. Ecol. 21, 381–390 (2017).
76. Frischknecht, R. & Jolliet, O. Global Guidance for Life Cycle Impact Assessment Indicators (UNEP/SETAC Life Cycle Initiative, Paris, 2016).
77. Hauschild, M. Z. et al. Identifying best existing practice for characterization modeling in life cycle impact assessment. Int. J. Life Cycle Assess. 18, 683–697 (2013).
78. Woods, J. S. et al. Ecosystem quality in LCA: status quo, harmonization, and suggestions for the way forward. Int. J. Life Cycle Assess. 23, 1995–2006 (2018).
79. Frischknecht, R. et al. Global guidance on environmental life cycle impact assessment indicators: progress and case study. Int. J. Life Cycle Assess. 21, 429–442 (2016).
80. Verones, F. et al. LCA framework and cross-cutting issues guidance within the UNEP-SETAC Life Cycle Initiative, J. Clean. Prod. 161, 957–967 (2017).
81. International Energy Agency. Energy Technology Perspectives 2010: Scenarios & Strategies to 2050 (International Energy Agency, 2010).
82. Ecoinvent, Life Cycle Inventory Database v2.2. http://www.ecoinvent.org/database/older-versions/ecoinvent-version-2/ecoinvent-version-2.html (2010).
83. Ecoinvent. http://www.ecoinvent.org/
84. Reddy, R., Hertwich, E. G. Life cycle assessment demonstrates environmental co-benefits and trade-offs of low-carbon electricity supply options. Renew. Sustain. Energy Rev. 76, 1283–1290 (2017).
85. NEEDS. LCA of Background Processes (New Energy Externalities Developments for Sustainability, 2008).
86. Popp, A. et al. Land-use protection for climate change mitigation. Nat. Clim. Change 4, 1095–1098 (2014).
87. Usubiaga, A., Acosta-Fernández, J., McDowell, W. & Li, F. G. N. Exploring the macro-scale CO2 mitigation potential of photovoltaics and wind energy in Europe’s energy transition. Energy Policy 104, 203–213 (2017).
88. Dale, M. & Benson, S. M. Energy balance of the global photovoltaic (PV) industry—is the PV industry a net electricity producer? Environ. Sci. Technol. 47, 3482–3489 (2013).
89. Pihenakis, V. & Kim, H. C. Land use and electricity generation: a life-cycle analysis. Renew. Sustain. Energy Rev. 13, 1465–1474 (2009).
90. Amann, M. et al. Cost-effective control of air quality and greenhouse gases in Europe: modeling and policy applications. Environ. Model. Softw. 26, 1489–1501 (2011).
91. Bijl, D. L., Bogaart, P. W., Kram, T., de Vries, B. J. M. & van Vuuren, D. P. Long-term water demand for electricity, industry and households. Environ. Sci. Policy 55, 75–86 (2016).

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Author contributions
G.L., E.G.H., A.A. and M.P. designed the research and scenarios; A.A., E.G.H. and T.G. performed LCA modeling; M.P., H.S.d.B., O.F., M.H., G.I., I.M., R.C.P., S.M., M.v.d.B., D.v.V. performed IAM scenario modeling work; F.H., B.L.B. and A.P. performed land-use modeling of bioenergy impacts; R.C.P. contributed grid and storage modeling; M.P., G.L. and A.A. performed IAM/LCA integration; G.L. and M.P. performed data analysis and prepared all figures; G.L. wrote the paper with input from all authors.

Competing interests
The authors declare no competing interests.

Additional information
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