Integrated life-cycle assessment of electricity-supply scenarios confirms global environmental benefit of low-carbon technologies

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Decarbonization of electricity generation can support climate-change mitigation and presents an opportunity to address pollution resulting from fossil-fuel combustion. Generally, renewable technologies require higher initial investments in infrastructure than fossil-based power systems. To assess the tradeoffs of increased up-front emissions and reduced operational emissions, we present, to our knowledge, the first global, integrated life-cycle assessment (LCA) of long-term, wide-scale implementation of electricity generation from renewable sources (i.e., photovoltaic and solar thermal, wind, and hydropower) and of carbon dioxide capture and storage for fossil power generation. We compare emissions causing particulate matter exposure, freshwater ecotoxicity, freshwater eutrophication, and climate change for the climate-change-mitigation (BLUE Map) and business-as-usual (Baseline) scenarios of the International Energy Agency up to 2050. We use a vintage stock model to conduct an LCA of newly installed capacity year-by-year for each region, thus accounting for changes in the energy mix used to manufacture future power plants. Under the Baseline scenario, emissions of air and water pollutants more than double whereas the low-carbon technologies introduced in the BLUE Map scenario allow a doubling of electricity supply while stabilizing or even reducing pollution. Material requirements per unit generation for low-carbon technologies can be higher than for conventional fossil generation: 11–40 times more copper for photovoltaic systems and 6–14 times more iron for wind power plants. However, only two years of current global copper and one year of iron production will suffice to build a low-carbon energy system capable of supplying the world's electricity needs in 2050.

land use | climate-change mitigation | air pollution | multiregional input–output | CO_2 capture and storage

A shift toward low-carbon electricity sources has been shown to be an essential element of climate-change mitigation strategies (1, 2). Much research has focused on the efficacy of technologies to reduce climate impacts and on the financial costs of these technologies (2–4). Some life-cycle assessments (LCAs) of individual technologies suggest that, per unit generation, low-carbon power plants tend to require more materials than fossil-fueled plants and might thereby lead to the increase of some other environmental impacts (5, 6). However, little is known about the environmental implications of a widespread, global shift to a low-carbon electricity supply infrastructure. Would the material and construction requirements of such an infrastructure be large relative to current production capacities? Would the shift to low-carbon electricity systems increase or decrease other types of pollution? Energy-scenario models normally do not represent the manufacturing or material life cycle of energy technologies and are therefore not capable of answering such questions. LCAs typically address a single technology at a time. Comparative studies often focus on a single issue, such as selected pollutants (7), or the use of land (8) or metals (9, 10). They do not trace the interaction between different technologies. Existing comparative analyses are based on disparate, sometimes outdated literature data (7, 11, 12), which raises issues regarding differences in assumptions, system boundaries, and input data, and therefore the comparability and reliability of the results. Metaanalyses of LCAs address some of these challenges (13, 14), but, to be truly consistent, a comparison of technologies should be conducted within a single analytical structure, using the same background data for common processes shared among technologies, such as component materials and transportation. The benefits of integrating LCA with other modeling approaches, such as input–output analysis, energy-scenario modeling, and material-flow analysis have been suggested in recent reviews (7, 15).

We analyze the environmental impacts and resource requirements of the wide-scale global deployment of different low-carbon electricity generation technologies as foreseen in one prominent climate-change mitigation scenario [the International Energy Agency's (IEA) BLUE Map scenario], and we compare it with the IEA's Baseline scenario (16). To do so, we developed an integrated hybrid LCA model that considers utilization of the selected energy technologies in the global production system and includes several efficiency improvements in the production system assumed in the BLUE Map scenario. This model can

Significance

Life-cycle assessments commonly used to analyze the environmental costs and benefits of climate-mitigation options are usually static in nature and address individual power plants. Our paper presents, to our knowledge, the first life-cycle assessment of the large-scale implementation of climate-mitigation technologies, addressing the feedback of the electricity system onto itself and using scenario-consistent assumptions of technical improvements in key energy and material production technologies.

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Data deposition: The life-cycle inventory data are available on the Norwegian University of Science and Technology website, www.ntnu.no/documents/10370/1021067956/Environmental+assessment+of+clean+electricity.

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address the feedback of the changing electricity mix on the production of the energy technologies.

We collected original life-cycle inventories for concentrating solar power (CSP), photovoltaic power (PV), wind power, hydropower, and gas- and coal-fired power plants with carbon dioxide (CO_2) capture and storage (CCS) according to a common format, and we provide these inventories in *SI Appendix*. Bioenergy was excluded because an assessment would require a comprehensive assessment of the food system, which was beyond the scope of this work. Nuclear energy was excluded because we could not reconcile conflicting results of competing assessment approaches (17). To reflect the prospective nature of our inquiry, the modeling of technologies implemented in 2030 and 2050 also contains several assumptions regarding the improved production of aluminum, copper, nickel, iron and steel, metallurgical grade silicon, flat glass, zinc, and clinker (18). These improvements represent an optimistic-realistic development in accordance with predictions and goals of the affected industries, as specified in ref. 18 and summarized in *SI Appendix*, Table S1. Technological progress in the electricity conversion technologies was represented through improved conversion efficiencies, load factors, and next-generation technology adoption to achieve the technology performance of the scenarios (see *SI Appendix* for details).

Results has two parts. First, low-carbon technologies are compared with fossil electricity generation without CCS to quantify environmental cobenefits and tradeoffs relevant for long-term investment decisions in the power sector. This comparison reflects the current state-of-the-art technology performance for both low-carbon and fossil systems. We examine impacts in terms of greenhouse gas (GHG) emissions, eutrophication, particulate-matter formation, and aquatic ecotoxicity resulting from pollutants emitted to air and water throughout the life cycle of each technology. We also compare the life-cycle use of key materials (namely aluminum, iron, copper, and cement), nonrenewable energy, and land for all investigated technologies per unit of electricity produced. *SI Appendix* contains a discussion of technology-specific results. To our knowledge, this analysis is the first to be based on a life-cycle inventory model that includes the feedback of the changing electricity mix and the effects of improvements in background technologies on the production of the energy technologies.

In the second part of *Results*, we show the potential resource requirements and environmental impacts of the evaluated technologies within the BLUE Map scenario and compare these results with those of the Baseline scenario. Our modeling is based on the installation of new capacity and the utilization of this capacity such that it is consistent with the BLUE Map scenario. It traces an important aspect of the transition toward a low-carbon energy system: that new capacity of low-carbon electricity generation technology is constructed using the existing electricity mix at any point of time. We quantify the requirements of bulk materials and the environmental pressures associated with the BLUE Map scenario over time and compare them with the Baseline scenario. We then compare results to annual production levels of these materials. In *Discussion*, we examine issues related to the presented work, in particular the implication of life-cycle effects on the modeling of mitigation scenarios and limitations with respect to the grid integration of variable renewable supply.

Results

Technology Comparison per Unit Generation. Our comparative LCA indicates that renewable energy technologies have significantly lower pollution-related environmental impacts per unit of generation than state-of-the-art coal-fired power plants in all of the impact categories we consider (Fig. 1 and *SI Appendix*, Table S5). Modern natural gas combined cycle (NGCC) plants could also cause very little eutrophication, but they tend to lie between renewable technologies and coal power for climate change (Fig. 1*A*) and ecotoxicity (Fig. 1*C*). NGCC plants also have higher contributions of particulate matter exposure (Fig. 1*B*). The LCA finds that wind and solar power plants tend to require more bulk materials (namely, iron, copper, aluminum, and cement) than coal- and gas-based electricity per unit of generation (Fig. 1 *G–J*). For fossil fuel-based power systems, materials contribute a small fraction to total environmental impacts, corresponding to <1% of GHG emissions for systems without CCS and 2% for systems with CCS. For renewables, however, materials contribute 20–50% of the total impacts, with CSP tower and offshore wind technologies showing the highest shares (*SI Appendix*, Fig. S1). However, the environmental impact of the bulk material requirements of renewable technologies (*SI Appendix*, Table S1) is still small in absolute terms compared with the impact of fuel production and combustion of fossil-based power plants (Fig. 1).

CCS reduces CO_2 emissions of fossil fuel-based power plants but increases life-cycle indicators for particulate matter, ecotoxicity, and eutrophication by 5–60% (Fig. 1 *B–D*). Both postcombustion and precombustion CCS require roughly double the materials of a fossil plant without CCS (Fig. 1 *G–J*). The carbon capture process itself requires energy and therefore reduces efficiency, explaining much of the increase in air pollution and material requirements per unit of generation.

Habitat change is an important cause of biodiversity loss (19). Habitat change depends both on the project location and on the specific area requirement of the technology. For example, PV power may be produced in pristine natural areas (high impact on habitat) or on rooftops (low impact on habitat). A detailed assessment of specific sites used for future power plants is beyond the scope of this global assessment. As an indicator of potential habitat change, we use the area of land occupied during the life cycle of each technology (Fig. 1*E*).

High land-use requirements are associated with hydropower reservoirs, coal mines, and CSP and ground-mounted PV power plants. The lowest land use requirements are for NGCC plants, wind, and roof-mounted PV. We consider roof-mounted PV to have zero direct land use because the land is already in use as a building. For ground-mounted solar power, we consider the entire power plant because the modules or mirrors are so tightly spaced that agriculture and other uses are not feasible in the unoccupied areas. Considering only the space physically occupied by the installation, the area requirements decrease by a factor of 2–3 compared with the values in Fig. 1*E* (8). For direct land use associated with wind power, we consider only the area occupied by the wind turbine itself, access roads, and related installations. We do not include the land between installations because it can be used for other purposes such as agriculture or wilderness, with some restrictions (20). If an entire land-based wind park is considered, land use would be on the order of 50–200 square meter-year/MWh (m^2a/MWh) (8, 20), which is higher than other technologies. We do not account for the use of sea area by offshore wind turbines.

Cumulative nonrenewable (fossil or nuclear) energy consumption is of interest because it traces the input of a class of limited resources. The current technologies used in the production of renewable systems consume 0.1–0.25 kWh of nonrenewable energy for each kWh of electricity produced (Fig. 1*F*). The situation is different for fossil fuel-based systems, for which the cumulative energy consumption reflects the efficiency of power production and the energy costs of the fuel chain and, if applicable, the CCS system.

Scenario Results. The BLUE Map scenario posits an increase in the combined share of solar, wind, and hydropower from 16.5% of total electricity generation in 2010 to 39% in 2050. The required up-front investment in renewable generation capacity

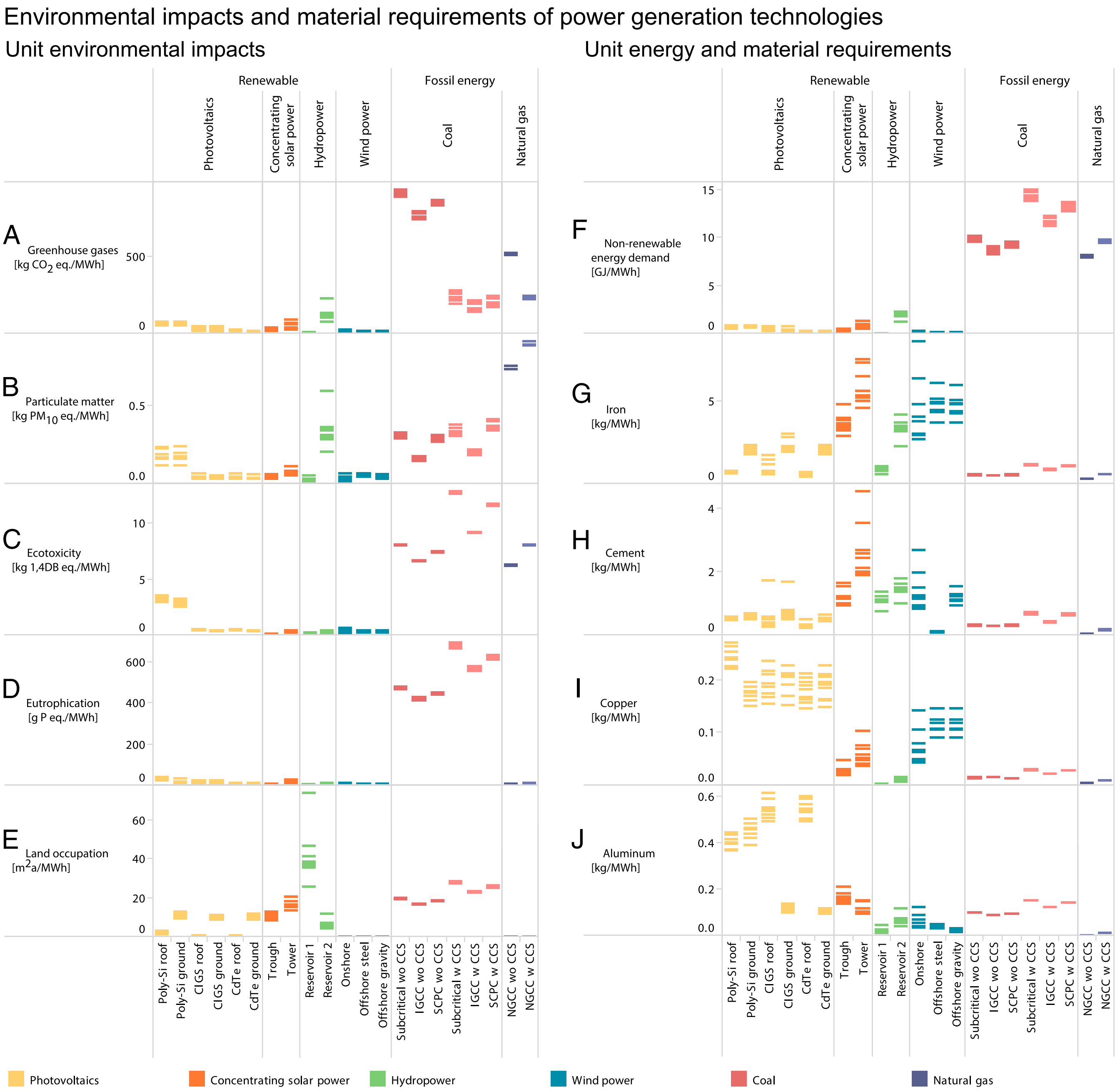

Fig. 1. A comparison of life-cycle environmental pressures and resource use per unit of electricity generated by different power-generation technologies in each of nine world regions. The left column shows four pollution-oriented indicators: (*A*) Greenhouse gases, (*B*) particulate matter exposure, (*C*) freshwater ecotoxicity, and (*D*) freshwater eutrophication. In addition, land occupation (*E*) is shown. The right column indicates nonrenewable primary energy demand (*F*) and the demand for materials (*G*–*J*). CCS, CO_2 capture and storage; CdTe, cadmium telluride; CIGS, copper indium gallium selenide; IGCC, integrated gasification combined cycle coal-fired power plant; NGCC, natural gas combined cycle power plant; offshore gravity, offshore wind power with gravity-based foundation; offshore steel, offshore wind power with steel-based foundation; reservoir 2, type of hydropower reservoir used as a higher estimate; SCPC, supercritical pulverized coal-fired power plant.

would require a combined investment of bulk materials of 1.5 Gt over the period 2010–2050, which is more than the total use of these materials in the Baseline scenario. Because of the need to install new renewable capacity, the material requirement of the BLUE Map scenario is from the outset higher than that of the Baseline scenario, even as the generation profiles are initially quite similar. The difference in material demand displayed in Fig. 2 *G*–*J* shows that the initial demand for iron and cement is mainly associated with wind and CSP installations whereas it is mainly PV driving additional copper demand. The BLUE Map scenario has a lower material demand associated with conventional coal-fired power plants without CCS, which is partly offset by the material demand from coal-fired power plants with CCS. The most important contributor to the material demand from coal-fired power plants is associated with producing and transporting the ∼500 kg of coal required per MWh of electricity generated.

The BLUE Map scenario would be able to keep the emissions of particulate matter and ecotoxicity stable despite the doubling of annual electricity generation from 18 petawatt hours per

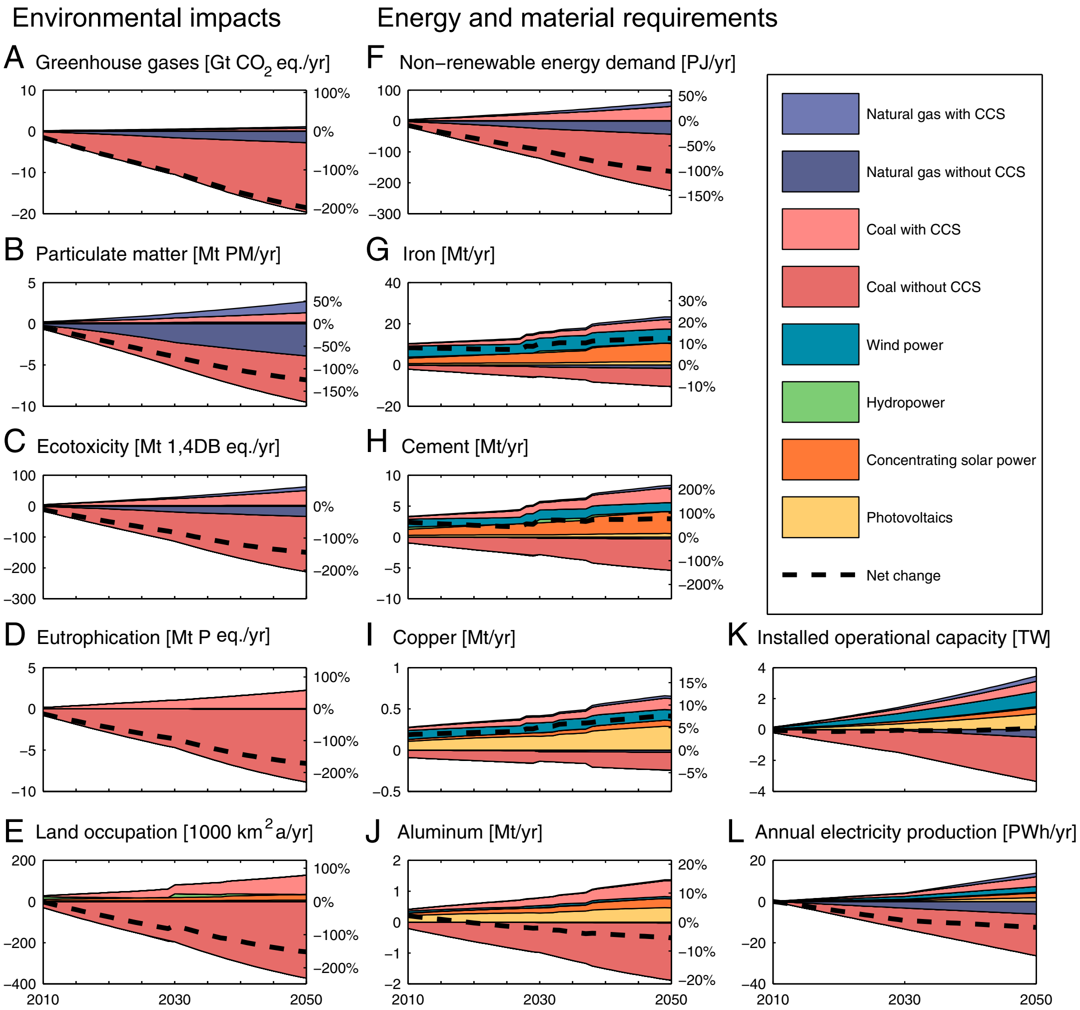

Fig. 2. (*A*–*L*) Environmental and resource implications of electricity generation following the IEA BLUE Map scenario instead of the IEA Baseline scenario, addressing impacts from the indicated power sources. The results show a reduction of pollution-related environmental impacts despite a doubling of electricity generation but a substantial increase of material consumption, especially copper. Left axes show absolute values. Right axes show the variation, in percentage, between these absolute values and the base levels in 2007. Note that the net change can reach values below −100% when the difference between the Baseline and BLUE Map scenarios is higher than the base 2007 levels.

annum (PWh/a) to 36 PWh/a for the technologies investigated. Compared with the situation in 2010, a substantial reduction in GHG emissions (from 9.4 Gt CO_2 eq. to 3.4 Gt CO_2 eq.) and eutrophication would be achieved (*SI Appendix*, Fig. S4). In stark contrast, the Baseline scenario would lead to a doubling of all pollution-related indicators even as new, highly efficient coal-fired power plants come online (*SI Appendix*, Fig. S3). The difference in pollution between the BLUE Map and Baseline scenarios would grow dramatically over time (Fig. 2) whereas the additional required material investment would rise only moderately. Such a development is the result of the growing dividend from the continuous investment in renewable generation capacity.

For the BLUE Map scenario, the higher material requirement per unit of renewable electricity and a projected increase in energy demands cause a substantial increase in material use (*SI Appendix*, Fig. S4). The overall material requirement per unit of electricity produced would be 2.3 kg/MWh compared with 1.2 kg/MWh for the Baseline scenario. That increase appears manageable in the context of current production volumes, the long lifetime of the equipment, and the ability to recycle the metals. Compared with material production levels in 2011, the construction and operation of the 2050 electricity system envisioned in the BLUE Map scenario would require less than 20% of the cement, 90% of the iron, 150% of the aluminum, and 200% of the copper, all relative to their respective 2011 production quantities (Table 1). Meeting copper demand could be problematic due to declining ore grades (21), and it would result in potential increases in the environmental costs of copper production (22, 23). Additional evidence for this conclusion is presented in *SI Appendix*.

Displacing fossil fuels through the widespread deployment of solar and wind energy could limit air and water pollution (Fig. 2). Over the study period (2010–2050), emissions of GHG connected to the power plants investigated are 62% lower in BLUE Map than they are in the Baseline Scenario whereas the particulate matter is 40% lower, freshwater ecotoxicity is almost 50% lower, and eutrophication is 55% lower. Furthermore, both cumulative energy consumption and land use are reduced. Our analysis might understate the cobenefits of climate-change mitigation in the form of pollution reduction because we assume the replacement of state-of-the-art fossil power plants with well-operating, modern emissions control equipment; the actual situation might be that emissions control equipment are functioning suboptimally or are altogether absent due to a lack of regulation.

Table 1. Cumulative material requirements for electricity production for the BLUE Map scenario

Material	Annual production (2011), Gt	Metal requirements to 2050, Gt	Ratio
Aluminum	0.045	0.067	1.5
Copper	0.013	0.029	2.2
Iron	1.5	1.3	0.87
Cement	3.4	0.52	0.15

The middle column provides an estimate of the volumes of materials that need to be produced to provide for the capital stock additions between 2010 and 2050 and the material requirements associated with operational inputs (fuels, transport, solvents, etc.) during the same period. The right hand column expresses these material requirements as a fraction of the 2011 production volume.

Further results on specific technologies, GHG emissions from material production, and the scenario analysis are presented in *SI Appendix*.

Discussion

Previous assessments of life-cycle impacts of electricity-generation technologies have used static LCAs (7, 11–15). Technologies are thus analyzed side-by-side, assuming current production technologies. We present an assessment based on an integrated, scenario-based hybrid LCA model with global coverage through the integration of the life-cycle process description in a nine-region multiregional input–output model. Integration of the life-cycle model, in which new technologies become part of the electricity mix and thus the life cycle of the same and other new technologies, addresses the interaction among technologies. Adopting a vintage capital model, the life-cycle stages of individual power plants are explicitly in time, also a novelty compared with current LCA practice. This previously unidentified type of modeling approach thus provides the ability to model the role of various technologies in a collectively exhaustive and mutually exclusive way. Only through this integration can the life-cycle emissions and resource use of energy scenarios be analyzed correctly. Further, we can assess the contributions of changes in the technology mix and improvements in the technology itself to future reductions of environmental impacts, as demonstrated in ref. 24.

The widespread utilization of variable sources such as solar and wind energy raises the question: what are the additional environmental costs of matching supply and demand? Grid-integration measures for variable supply, such as the stand-by operation of fossil fuel power plants, grid expansion, demand-response and energy storage (25–27), result in extra resource requirements and environmental impacts (28). The challenges of balancing supply and demand are not yet severe in the BLUE Map scenario, in which variable wind and solar technologies cover 24% of the total electricity production in 2050, but balancing becomes a serious concern later in the century in the many mitigation scenarios investigated by ref. 2 that rely on a higher share of variable renewables. In the BLUE Map scenario, the capacity factor of fossil fuel-fired power plants without CCS is reduced from 40% in 2007 to 19% in 2050 for natural gas, and from 65% to 30% for coal for the same period, but IEA provides no information on emissions associated with spinning reserves, or ramp-up and ramp-down. The National Renewable Energy Laboratory's (NREL) Western Wind and Solar Integration Study indicates that increased fossil power plant cycling from the integration of a similar share of variable renewables may result in only negligible increases in greenhouse gas emissions compared with a scenario without renewables. It may also result in further reductions in nitrogen oxide emissions and increases in SO_2 emissions equal to about 2–5% of the total emissions reduced by using renewables. In a study investigating an 80% emission reduction in California, electricity storage requirements become significant only at higher rates of renewable energy penetration (26). See *SI Appendix* for further information on grid integration of renewables. Additional research on different options for the system integration of renewables and its environmental impact is required to determine the share of renewables most desirable from an environmental perspective.

Our analysis raises important questions. (*i*) What would similar analyses of other mitigation scenarios look like? Thousands of scenarios have been collected in the Intergovernmental Panel on Climate Change (IPCC) mitigation scenario analysis database (4). These scenarios use a combination of energy conservation, renewable and nuclear energy, and CCS. Our analysis suggests that an electricity supply system with a high share of wind energy, solar energy, and hydropower would lead to lower environmental impacts than a system with a high share of CCS. (*ii*) How can scenarios for a wider range of environmental impacts be routinely assessed? Endogenous treatment of equipment life cycles as considered here in energy-scenario models has not yet been achieved. Options are either to (*a*) include some simplified assessments in energy scenario models, using the unit-based results from our analysis in the scenario models, or to (*b*) conduct a postprocessing of scenario results in the manner done for this study. The advantage of option *a* is that life-cycle emissions could be considered in the scenario development, thus affecting the technology choice; the advantage of option *b* is the ability to include feedbacks and economy-wide effects in the calculation of life-cycle emissions. (*iii*) Will fundamental differences in energy systems such as those between mitigation and baseline scenarios lead to significant changes to the supply and demand for many products (e.g., fuels and raw materials)? It is clear that there will be effects on the supply and demand of goods both due to different energy policies (e.g., carbon prices) and because of differences in the demand and supply of resources (e.g., iron or coal) to the global economy. Such indirect effects were outside of the scope of this study, but they could be considered in a consequential analysis (29).

Conclusions

Our analysis indicates that the large-scale implementation of wind, PV, and CSP has the potential to reduce pollution-related environmental impacts of electricity production, such as GHG emissions, freshwater ecotoxicity, eutrophication, and particulate-matter exposure. The pollution caused by higher material requirements of these technologies is small compared with the direct emissions of fossil fuel-fired power plants. Bulk material requirements appear manageable but not negligible compared with the current production rates for these materials. Copper is the only material covered in our analysis for which supply may be a concern.

Materials and Methods

Using a uniform data-collection form, we collected foreground data describing the life-cycle inventory of the analyzed technologies. For more information on inventory data and modeling assumptions, see *SI Appendix*. These foreground data were linked to the ecoinvent 2.2 life-cycle inventory database (30), which provides information on many input processes such as materials and manufacturing, and the EXIOBASE input–output database (31), which provides emissions estimates for inputs of services and highly manufactured goods. We modeled nine world regions to perform a regional sensitivity analysis. Exogenous scenario parameters and electricity mixes were taken from the IEA scenarios (16), which represent the same nine world regions. Impact assessment was conducted using ReCiPe version 1.08 (32). To specify resource use, cumulative nonrenewable energy demand, land use, and the use of iron, aluminum, and copper (metal content of the ore or scrap used) were specified. To complement environmentally important material flows (33), we also quantified the amount of cement required. Life-cycle inventories for this comparative analysis were built based on our original work and a review of scientific literature on the selected technologies. To obtain a better representation of the fugitive methane emissions related to fossil-fuel extraction, ecoinvent 2.2 was updated with the fugitive emissions factors published in ref. 34, which is in line with other recent estimates.

To develop the scenarios of emissions and resource use presented in Fig. 2 and *SI Appendix*, Figs. S3 and S4, we identified the timing of capacity additions, operations, repowering, and removal of power plants in the scenario (35). We delineated the life-cycle impacts into these phases. Therefore, the figures reflect the timing of resource use and emissions, not the timing of electricity generation. The inventories associated with each life cycle step reflect the technology status and electricity mix of the year in question. The IEA provides electricity production by technology group (e.g., PV), so we estimated intratechnology group market shares [e.g., the division of the PV market among Si, cadmium telluride (CdTe), and copper indium gallium selenide (CIGS) technologies]. As of 2010, 90% of the PV market in terms of produced electricity was silicon-based whereas the remaining share consisted of thin-film modules. The share of silicon-based modules gradually decreases to 20% in 2050. Half of the electricity produced by CSP was assumed to be generated from central receivers systems; the other half was assumed to be from parabolic troughs. This allocation remained consistent throughout the scenario time frame. Hydropower plants were represented by two different dams modeled after the Baker River Basin dams in Chile. Unit results show high variability, even within the same river basin. Wind power plants were assumed to contain conventional gearbox-equipped wind turbines because reliable LCA data on rare earth metal use in direct drive wind turbines could not be obtained. Offshore wind farm production was modeled as an even mix of gravity-based and steel foundation turbines. The market mix of coal-combustion technologies was modeled after real production data for China, India, and the United States. A global average was applied for other regions. Due to high uncertainty of coal market share estimates, we used the 2010 mix for 2030 and 2050. We assumed all gas-fired power plants used combined cycle technology.

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