Supporting Information (SI)

Title:

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

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MATERIALS AND METHODS

Goal and scope

This work aims to provide insight on the comparative environmental impacts and resource use of electricity generation technologies. Furthermore, this study assesses the effect of a wide-scale adoption of technologies with low greenhouse gas emissions in contrast to the continued utilization of conventional fossil technologies. The BLUE Map and Baseline scenarios from the International Energy Agency (IEA) Energy Technology Perspectives (1) were used to provide information on the total rate of potential deployment of various electricity generation technologies in nine world regions. The BLUE Map scenario is a climate change mitigation scenario moving towards the 2°C target and requires stringent climate policies, whereas the Baseline scenario does not assume any additional policy adoptions. We compared different technologies in terms of impacts per unit of electricity (kWh) delivered to the grid. This basis for comparison does not imply that we considered the electricity delivered by the different generation sources to be interchangeable or functionally equivalent; the matching of electricity supply and demand is performed at the level of an entire electricity system and not at the individual technology level. In the discussion section of this SI and the main manuscript, we address the issue of system balancing for the environmental performance of the BLUE Map scenario.

Inventory data structure

IEA Energy Technology Perspectives Scenarios

The following electricity generation technologies are part of the IEA's BLUE Map and Baseline scenarios: coal, coal equipped with carbon dioxide capture and storage (CCS), natural gas, natural gas with CCS, biomass and waste, biomass and waste with CCS, oil, nuclear, hydropower, wave and tidal, geothermal, solar photovoltaics (PV), concentrating solar power (CSP), and onshore and offshore wind power. The scenario model represents nine world regions: China, India, OECD Europe, OECD North America, OECD Pacific, Economies in transition, Latin America, Asia, and Africa and Middle-East. The life cycle inventory model has been adapted so as to match this regional classification. We obtained the following information from the scenarios: electricity production, installed capacity, and fuel efficiencies broken down by technology and region for 2010, 2030 and 2050.

Energy technology product systems (foreground)

In LCA, *foreground* refers to the system including the processes that are linked directly to the functional unit and for which primary information has been collected in the assessment. *Background* processes are those commonly used processes already described in readily available databases, like production of basic materials and transport by truck, rail, or ship. In hybrid assessment, the background consists of an input-output database and possibly a generic life cycle inventory database (2).

In modeling prospective, scenario-based LCA results, the model needs to reflect direct improvements or changes to the technology in question. We used the following: (1) industry road maps, (2) technology learning curves, and (3) expert opinion. Below, in the "Life cycle inventories of energy technologies" section, we describe the life cycle inventories representing the energy technology systems investigated in this paper.

Life cycle inventory database (background)

Process life cycle inventories trace the physical inputs and outputs of materials and energy of the processes in the life cycle. This approach allows for adjustment in degree of detail and specificity. Furthermore, in the context of scenario modeling, employing physical, process-based life cycle inventories (as opposed to economic, input-output-based inventories) becomes an advantage as process improvements can usually be characterized in terms of improved physical efficiency, i.e., direct emission reduction, variations in resource use, reduced losses, or enhanced use of recycled material and recycling rates. These changes directly affect the physical inventory of inputs and outputs, as they mostly rely on simple mass balance principles.

We utilized the *ecoinvent* 2.2 database (3), the most widely used life cycle inventory database. While the database originally reflects European production technologies, a widely used adaptation to North America exists. We updated and extended the database with several life cycle inventories prepared for the update to *ecoinvent 3* (4), but we could not include the new database as we conducted this work before the release of *ecoinvent 3*. We adapted the *ecoinvent* database to other regions by adjusting electricity mixes.

Multiregional input-output model (background)

We constructed a nine-region multi-regional input-output (MRIO) model from the more detailed EXIOBASE MRIO tables (5) to match the nine regions of the IEA Energy Technology Perspectives model (1).

Impact assessment

Impact assessment is the step in a standard life cycle assessment (LCA) in which emission and resource flows from the life cycle inventory are combined into a smaller set of environmental impact indicators. These indicators are developed using characterization factors derived from a modeling of environmental mechanisms. Greenhouse gas (GHG) emissions, for example, can be aggregated in terms of the global warming potential (GWP). One of the most prominent and widely used impact assessment methods is ReCiPe version 1.08 (6), which assesses impacts in terms of midpoint indicators representing common environmental mechanisms such as the formation of fine particulate matter and radiative forcing. The particulate matter (PM) formation potential (7) includes both direct emissions of fine particulates (<10 μm) and the formation of particulates from precursors such as SO_2, NO_x, sulfate, and ammonia. PM exposure has the highest human health impacts of any pollution type (8). Freshwater eutrophication addresses the addition of nutrients to freshwater bodies (9). Freshwater ecotoxicity was chosen as an indicator to represent a wider suite of toxicity indicators (10), because it is fairly mature given the wide availability of toxicity data for aquatic species.

Resource assessment

We quantified bulk material flows of iron, aluminum, copper, and cement required for the technologies analyzed. The metal flows should be understood as the metal content of the ore extracted and utilized for primary production and of the waste streams utilized for secondary production. These materials are used for their structural and conductive properties. The production of these materials causes high environmental impacts (11, 12). Allwood et al. (11) find that iron and steel, aluminum, and cement together cause about 50% of anthropogenic CO_2 emissions from the industrial sector, although plastic (5%) and paper (4%) are also important. However, plastic and paper have much shorter average lifetimes and their use in energy technologies is not particularly high. The environmental significance of copper is related to its toxicity (13).

We quantified the flow of iron as an indicator reflecting the use of iron both in its unalloyed form, (e.g., magnetic iron for generators and transformers), and in steel. The organization of present life cycle inventory databases made it difficult to clearly identify the refined metals in their different alloys. We derived the primary metal demand from the *ecoinvent* background from the environmental interventions that list the resource requirements. Secondary production was calculated from the final output of selected *ecoinvent* process flows. The metal contributions from the input-output background were calculated from figures on quantities of ore extracted (5), assuming the following metal contents of ore: iron ore, 50%; bauxite and aluminum ores, 20%; and copper ore, 1% (14).

Cement was quantified because its production causes substantial environmental impacts; not all limestone is calcinated and concrete may contain different amounts of cement. As a result, cement is a superior indicator for environmental impact over limestone and concrete. We derived cement flows from five process flows in *ecoinvent* and an EXIOBASE environmental extension for limestone, gypsum, chalk and dolomite, representing the primary inputs to cement production. The use of the extension for limestone, gypsum chalk and dolomite is necessary as there is no physical equivalent of cement use in the (monetary) EXIOBASE database. This leads to a possible overestimation of the cement requirements, as potential losses would not be accounted for. In most inventories, main inputs are from the *ecoinvent* background, whereas the contribution from the input-output background remains small.

We quantified total non-renewable primary energy as an additional resource indicator called cumulative energy demand. We calculated the indicator by multiplying the amount of fuel extracted with the higher heating value of fossil fuels and the producible heat from uranium ore using current best technology, including recycling of the plutonium (15). We also quantified total land occupation measured in land area multiplied by the time that this land area is occupied.

Model description

We developed a life cycle assessment model capable of addressing the full-scale introduction of one or several technologies on the macro-level, taking a scenario approach. The model, named THEMIS[1], uses an integrated hybrid approach, combining foreground information on the technologies in question, a background LCA database of generic processes such as materials and transport, and MRIO tables. We produced versions of these tables for nine world regions for the years 2010, 2030 and 2050 based on a range of scenario assumptions for the improvement of technologies. Here we first present the general model characteristics and structure. In subsequent sections, we present the separate parts that are assembled to constitute the final model, and how they are adapted to scenario modeling: energy technology (foreground) systems, background life cycle inventory database and MRIO tables, vintage capital model, and exogenous scenario assumptions.

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[1] Technology Hybridized Environmental-economic Model with Integrated Scenarios

General model characteristics

THEMIS integrates four main features. First, its core is a hybrid LCA input-output framework, allowing the combination of physical process models, describing, for example, the production of materials, and an input-output model that offers a complete description of the entire economy including, for example, accounting and business services usually not described in process life cycle inventories. The hybrid LCA hence allows for a more complete description of the life cycle inventories (16-18). Second, we modeled the deployment of electricity generation technologies; we replaced existing technology mixes with those obtained from scenario analysis for each of the nine regions represented by the IEA energy scenario model. We then fed these future electricity mixes back to the process and input-output background, thereby capturing the changes in the life cycle impacts of for example materials and business services resulting from the changed electricity mix. Third, we modeled the transition from a current to a 2050 electricity mix year-by-year, utilizing a vintage capital model to trace the composition of electricity generation technologies. Fourth, we utilized exogenous scenario assumptions on the improvement of technologies, including increased energy efficiency and capacity factors, as well as changed material production technologies. A key insight of energy scenario modeling is that energy technologies change through frequent application. Research, development, and learning-by-doing lead to reductions of costs and, most likely, of resource requirements and thus environmental impact per unit energy produced (19, 20).

General model structure

We utilized a general structure of hybrid life cycle inventory modeling (2) with temporally explicit life cycle inventory as first described in (21). As a novel element in this work, we integrated the results of our foreground electricity production technologies back into the economy, as suggested in (22). Equations (1) and (2) display the notations used to describe the technology matrix and its associated variables.

$$A(t) = \begin{pmatrix} A_{ff}(t) & A_{fp}(t) & A_{fn}(t) \\ A_{pf}(t) & A_{pp}(t) & A_{pn} \\ A_{nf}(t) & A_{np} & A_{nn} \end{pmatrix} \tag{1}$$

$$F(t) = \begin{pmatrix} F_f(t) & F_p(t) & F_n \end{pmatrix} \tag{2}$$

$A(t)$ and $F(t)$ are the technology and stressor (or factor) matrices, respectively. A represents the exchanges between processes in both physical and monetary terms; the index f describes a physical foreground process, p a physical background process and n an economic input-output process. There is no linkage between physical (A_{pp}) and economic (A_{nn}) databases, thus $A_{np} = A'_{pn} = 0$. F contains coefficients describing the emissions and resource consumption per physical or monetary unit.

Vintage capital modeling

Dynamic aspects of the model were reflected through the way power system capital stocks were modeled. We distinguished life cycle inventories for up-front, operational and decommissioning inputs for power plants and employed a vintage capital stock model (23) to calculate requirements and impacts of power generation in the year these occur (Fig. 2 in the main manuscript and Figs. S3 and S4). The breakdown of direct inputs into life cycle stages is embodied in equation (3), where $y_{start}(t)$ is a column vector representing up-front inputs in year t, $y_{oper}(t)$ operations inputs in year t and $y_{end}(t)$ decommissioning inputs in year t, for any given power generation technology and region. $y_{start}(t)$ and $y_{end}(t)$ are measured on a per added/decommissioned capacity basis (in units of, e.g., t MW^{-1}), while $y_{oper}(t)$ gives average annual operations inputs (in units of, e.g., t MW^{-1} yr^{-1}).

Further, we established time series of new capacity additions, operational capacities, repowering of existing capacity and capacity removal based on the future capacity trajectories described in the BLUE Map and Baseline scenarios respectively. In equation (3), $K_{new}(t)$, $K_{repow}(t)$ and $K_{decom}(t)$ give the added, repowered and decommissioned capacities, respectively, in year t, and $K_{oper}(t)$ the average total capacity in operation over year t. Repowering was modeled as 50% of a new capacity addition, and hence the factor 0.5 appears in the second term on the right-hand side of equation (3). This simplifying assumption has only very small (for all pollution-oriented indicators as well as for land use and energy demand) or modest (for materials) influence on final results. The term on the left-hand side of equation (3), $\tilde{y}(t)$, represents global, absolute inputs in year t, and is the sum of inputs when new plants are built (first term on right-hand side of equation (3)), and when existing plants are repowered (second term), used (third term) or repowered (fourth term).

$$\tilde{y}(t) = y_{start}(t)K_{new}(t) + 0.5y_{start}(t)K_{repow}(t) + y_{oper}(t)K_{oper}(t) + y_{end}(t)K_{decom}(t) \qquad (3)$$

$$\text{for } t = \{2010, \dots, 2050\}$$

Absolute emissions and resource use were then calculated year-by-year:

$$\tilde{e}(t) = F(t)\big(I - A(t)\big)^{-1}\tilde{y}(t), \text{for } t = \{2010, \dots, 2050\} \tag{4}$$

$\tilde{e}(t)$is a column vector giving total emissions and resource use results (e.g., amount of carbon dioxide emissions), F is a matrix of emission or resource load intensities by activity (e.g., carbon dioxide directly emitted by power stations), A and F are the technology and stressor (or factor) matrices, respectively, and I is the identity matrix.

Scenario-based assumptions about the improvement of background technologies

As noted above, THEMIS combines life cycle descriptions of individual power generation technologies, a process-based LCA database (3) and MRIO tables (5). THEMIS then adapts the data to represent important regional differences and changes over time in key processes or sectors; these adaptations include changing the electricity mix depending on region and year, and incorporating scenarios for efficiency improvements in key industrial processes. The key industrial processes selected for adaptations are aluminum, copper, nickel, iron and steel, metallurgical grade silicon, flat glass, zinc, and clinker. Table S1 shows the modifications brought to the energy inputs of these industrial processes in the *ecoinvent* database, based on the "optimistic realistic" set of parameters developed in the NEEDS project (24). The overarching assumption for the optimistic realistic scenario is: "the pathway of technology development is as far as possible according to prediction and goals of the industry that seem reasonable to be achieved" (24). The optimistic realistic scenario also includes a second assumption regarding electricity mixes, which was replaced instead by the assumptions of the IEA scenarios in the present model.

Life cycle inventories of energy technologies

In this section, we describe the life cycle inventories for concentrating solar power (CSP), photovoltaic (PV) power, wind power, hydropower, and gas- and coal-fired power plants with and without CCS collected for this work. We did not collect original life cycle inventories for oil-fired power plants, combined heat and power plants, bioenergy, or nuclear energy and hence do not present an analysis for these technologies. Oil-fired power plants and combined heat and power plants were not considered to be important in future climate change mitigation scenarios. Modeling bioenergy would require a separate scenario of the food demand and land use cover to understand how biomass would be produced and assess the land use related impacts, which is beyond the scope of this paper. For nuclear energy, we could not explain the large gap between process and economic input-output based inventory results and hence did not feel confident enough in the results we obtained. These technologies do occur in our background and *ecoinvent* (25) is used to describe the impact of these technologies on the electricity mix in the life cycle inventory modeling.[2]

Photovoltaics

Life cycle inventories were compiled for three major solar photovoltaic (PV) technologies: polycrystalline silicon (poly-Si), cadmium telluride (CdTe) and copper indium gallium selenide (CIGS) photovoltaic modules. The following lifetimes were assumed: 25 years for poly-Si and 30 years for CdTe and CIGS. The impacts of electricity produced by both utility-scale ground-mounted systems (26) and residential and commercial roof-mounted systems were considered given the prevalence of both applications in the BLUE Map scenario. Thin-film CdTe and CIGS data were collected from the National Renewable Energy Laboratory (NREL) manufacturing cost models (27-29). The models collect manufacturing information directly from solar PV manufacturers in the United States and use the data to estimate current and future photovoltaic costs per unit energy delivered as a result of conversion efficiency increases and improved material efficiency. Chinese production data were collected in an original research effort and used to represent poly-Si PV, which is the most common PV module technology, given that China maintains the majority of the global crystalline silicon production capacity (30). Metallurgical grade and solar grade (SOG) silicon production data were gathered from two factories in the Sichuan and Jiangsu provinces of China, and data for remaining production steps were mainly gathered from Company A, an international PV system integrator with several important suppliers in China (31, 32). Technological improvements were modeled based on the NREL manufacturing costs models and technology roadmaps and are summarized in Table S2 (27-29, 33). Balance of system (BOS) components were modeled based on information from Mason & Fthenakis' assessment of ground mounted systems (26) and *ecoinvent* data for roof mounted systems (34).

Decommissioning was accounted for in only the ground-mounted photovoltaic systems, and was assumed to amount to 10% of the energy requirements of the construction phase. Infrastructure connecting the system to the grid was also included, with the assumption that 50 km of medium voltage grid would be necessary to link up one ground-mounted photovoltaic plant to the network. The grid connection was modeled after (35).

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[2] The input data to the life cycle inventory modeling, documenting the foreground processes, are available at http://www.ntnu.no/documents/10370/1021067956/Environmental+assessment of+clean+electricity

Concentrating solar power

Concentrating solar power (CSP) is a fairly novel technology, with only 2.5 GW of existing installed capacity in 2012, compared with 100 GW for PV and 280 GW for wind (36). As of 2010, parabolic trough was the dominant CSP technology, followed by power towers (central receiver plants). Power towers are seen as a promising solar thermal option, due to the high operational temperatures and efficiencies that can be achieved (37). This study modeled both parabolic trough (38) and central receiver technologies (39, 40) to represent current and future available technologies. Parabolic trough and central tower technologies infrastructure inventories were built from hypothetical plants of Daggett, California (41) and Tucson, Arizona in the USA (40), respectively. We assumed a 30-year lifetime for both types of CSP. Decommissioning was accounted for in the two concentrating solar power systems, and was assumed to amount to 10% of the energy requirements of the construction phase. Both concentrating solar power plants were assumed to be connected to the grid via 50 km of medium voltage overhead power line, modeled after (35). Key data for the two plants are given in Table S3.

Operational inputs cover the consumption of heat transfer fluid (HTF) and water for the water cooling system for the trough plant. For the trough case, the HTF was assumed to be Therminol VP-1, a mixture of diphenyl oxide (DPO, 73.5%) and biphenyl (26.5%) (41). The typical parabolic trough design uses synthetic oil HTF combined with an indirect molten salt storage system that typically stores energy equivalent to 6-7.5 full load hours. For the tower design, a molten salt HTF and storage medium is assumed (40).

Wet cooling was assumed for the parabolic trough plant and dry cooling for the central tower plant, in accordance with the reference plant designs adopted in (40, 41). In reality, the preferred cooling technology (dry or wet) is very location-dependent for both parabolic trough and central tower designs. The only limitation to the inexpensive wet cooling option is water availability in some regions of the world. Dry cooling may save about 90% of water consumption (42), but is more energy-penalizing than wet cooling, which consumes virtually no energy. Water use is generally a major issue for CSP, in part because the most suitable sites for CSP tend to be located in arid or semi-arid regions.

Hydropower

The life cycle inventory data for hydropower came from several case studies of reservoir hydroelectric plants located in Chile, where rivers are mostly fed by melting ice from highlands (43). The cases are from a large hydroelectric complex on the Baker and Pascua river basins, between latitude 47° and 49°S in the Patagonia region, involving 5 reservoir plants and one pass-through, with a total installed capacity of approximately 2.76 GW. The approach included the construction process, building materials, machinery, electric generators, transportation, connection to grid and decommissioning. Data were obtained from primary sources and official environmental reports (44). The assumed lifetime was 80 years.

The inventory data do not show a direct correlation between land occupation and installed power, due to differences in hydrology. Additionally, dam size and height, and building material-specific requirements proved to be highly dependent on local topographical features. Transport requirements for the plants differed significantly. Decommissioning was accounted for in both hydropower systems and was assumed to be equivalent to amount to 10% of the energy requirements of the construction phase. In the same fashion as in the other renewable inventories, a 50 km-long connection to an existing grid was assumed, modeled as a medium voltage power line, with data from (35).

The design of hydropower plants and hence their life cycle impacts depend significantly on local factors. Indeed, in addition to the basin topographical features mentioned above, consideration must be given to the organic matter content of the water system. In this respect, it must be mentioned that cold high mountain Andean rivers exhibit a supersaturated oxygen level, neutral pH, low temperature and conductivity and negligible organic matter content (44). Thus, methane generation due to anaerobic digestion should be low compared to sites where a high organic matter load constitutes a considerable carbon source for biological processes, as shown in the methane emissions reported in the literature. One estimate is that the global average methane emissions from hydropower are 3 g CH_4/kWh (45) and are strongly correlated to reservoir area per unit power produced and weakly correlated to the natural biomass productivity of the area in question.

Wind power

Assumptions and data were to a large extent adopted from (21) and (46). The technology descriptions cover land-based and offshore systems described in terms of their general characteristics in Table S4. We assumed longer lifetimes offshore than onshore (Table S4) due to generally less turbulent winds, and thus less stress on turbines, at offshore sites. We distinguished between two offshore systems depending on whether foundations are made of steel, comprising 50% assumed market share or concrete, comprising the remaining 50%.

We assumed that the land-based and offshore wind technology descriptions to a satisfactory degree were representative of future developments toward 2050 when increases in wind load factors are taken into account. This simplification overlooked the introduction of different or new material solutions such as relatively increased or reduced use of glass, carbon or natural fiber reinforcement in rotor blades, or towers made of concrete. We also ignored the possible implementation of different design types (e.g., floating wind power plants, drive train configurations using permanent magnets made of rare earth elements), impacts of changing site characteristics (e.g., taller towers or offshore developments in deeper waters or farther from shore as suitable good wind sites become increasingly scarce), and scaling effects as wind turbines become ever larger. At the same time, the current inventory data set represents modern, large wind turbines and wind power plants. With the exceptions of rare earth elements and carbon fiber, it covers the spectrum of important material types involved in component manufacturing in coming decades. We do not anticipate radically different technologies becoming widespread before 2050.

Land use includes the area permanently occupied by infrastructure, excluding spacing between units and temporary land use, and excluding seabed or water surface area for offshore projects. We assumed land-based projects require 2.7 km^2/GW, which is the average permanent area occupied by infrastructure as found in a survey (47).

Rotor, hub, nacelle, and tower total weights were from (21) (onshore case) and (48) (offshore). Foundation weights were from (21) and (46). Internal underground or submarine cables connect the wind turbines to a substation; external underground or submarine cables or overhead lines serve as transmission links to an existing grid; Table S4 contains the assumed connection lengths. We established material and energy inputs for all components based on (21, 35, 46, 49, 50).

The installation, operations and maintenance (O&M) and end-of-life stages include transport and on-site operations. For the onshore case, we adopted the physical inventories of (21) for installation, and O&M. Decommissioning is assumed to equate 10% of the physical inputs for installation. Similarly, the inventories for offshore wind farms were based on (46). Finally, for onshore and offshore projects, we included supply of spare parts at replacement rates as in (46).

Fossil fuel based power with and without carbon capture and storage

We investigated four types of fossil fuel power plants, both with and without CCS. These were subcritical pulverized coal (SbC), supercritical pulverized coal (SC), integrated gasification combined cycle power plant (IGCC), and natural gas combined cycle power plant. For the CCS, we considered post-combustion capture using monoethanolamine and precombustion capture using Selexol. Detailed power plant designs were taken from reports of the US National Energy Technology Laboratory (51-55) and each plant is considered state-of-the-art. When information was insufficient, we took additional data from the peer-reviewed literature (56-58). Each plant was assumed to have a lifetime of 30 years. CO_2 capture efficiency is 90% for all power plants. The energy requirements of the CO_2 capture processes resulted in an efficiency penalty. In this study, the efficiencies of the respective power plants both with and without CCS were based on lower heating value (LHV) and are listed in Table S5 for the years 2010, 2030 and 2050. An increase in efficiency was assumed for the supercritical, integrated gasification and natural gas technologies (59). As one of the latest designs of subcritical technology was modeled here and newly built infrastructure will be most likely of the supercritical or IGCC variant, we assumed that efficiency improvements for subcritical technology would be marginal and therefore future efficiencies of this technology in the electricity mix will equal the 2010 efficiency.

The foreground modeling of the fossil fuel inventories included the upstream processes of fossil fuel extraction and subsequent transport of the fuel to the power plant. For the sake of comparison, it was assumed that coal is transported by rail over a distance of 330 km from the excavation site to the power plant. The *ecoinvent* process *hard coal, at mine* (region North America) was used as proxy for the coal extraction process (60). Natural gas was transported through an offshore pipeline with a length of 1000 km. The *ecoinvent* process *natural gas, at production* (region North America), with updated fugitive methane emissions (61), was used as proxy for the natural gas extraction process (60). Decommissioning accounted for all fossil fuel power systems, and was assumed to be equivalent to 10% of the energy requirements of the construction phase. Connection to an existing grid was modeled by a 30 km long medium-voltage overhead line, modeled after (35).

For the CCS cases, the following unit processes were included: on-site CO_2 capture and compression infrastructure, CO_2 transport pipeline, CO_2 injection well and the on-site CO_2 storage operation. After capture, the CO_2 was compressed to 150 bars and transported 150 km by pipeline to an underground formation at 1200 m depth. Under these conditions, intermediate CO_2 booster stations are not required. CO_2 leakage rates from transport were based on a rescaling of data previously published in the literature (62) and varied between 184.5 t CO_2/year for the natural gas plant and 496.5 t CO_2/year for the subcritical coal fired power plant. We assumed that no booster compression is required at the wellhead and that there was no leakage of CO_2 from the storage reservoir.

ADDITIONAL RESULTS AND DISCUSSION

Fig. 1 (in the main text) shows the results according to the ReCiPe method (6) for the 21 technologies, in 2010 in each of the nine world regions. The reader can further explore Fig. 1 online[3], looking at individual regions or selecting fewer technologies. Prospective results for 2030 and 2050 are also presented there. Fig. S2 shows the median contribution of the production of four material types to life cycle greenhouse gas emissions under the BLUE Map scenario assumptions. Iron production is the main contributor in all cases (0.16–5.5 g CO_2 eq./kWh), followed by cement (27 mg–2.0 g CO_2 eq./kWh), aluminum (8.5 mg–1.6 g CO_2 eq./kWh) and copper (0.86 mg–0.18 g CO_2 eq./kWh). Low-carbon electricity technologies have the highest relative share of emissions coming from the production of these four materials. Concentrating solar power shows the highest absolute values (4.0–7.0 g CO_2 eq./kWh), with wind power at 3.8–4.3 g CO_2 eq./kWh and photovoltaics at 2.1–3.3 g CO_2 eq./kWh.

Detailed results of the scenario analysis are presented in Fig. S3 and Fig. S4. The figures show the global absolute results for five ReCiPe midpoint impact categories (greenhouse gas emissions, particulate matter emissions, freshwater ecotoxicity, freshwater eutrophication and land use), non-renewable cumulative energy demand, material requirements (iron, cement, copper and aluminum), annual capacity increase, installed operational capacity and electricity production. Fig. 2 (in the main text) displays the difference in the same indicators for the scenarios displayed in Fig. S3 and Fig. S4.

Table S6 shows the results of a larger range of midpoint impact indicators; a selection of these is presented in Fig. 1 (in the main text). The table indicates that the overall pattern of low pollution of renewable compared to fossil technologies identified for the three indicators discussed in the main manuscript also holds for a larger set of indicators.

Technology-level results

Photovoltaics

PV electricity production depends on solar irradiation and module efficiency. Life cycle emissions for all PV technologies have steadily improved as a result of increased module efficiency and reduced material requirements of PV modules (20). LCAs have consistently shown that non-renewable energy use and life cycle GHG emissions of electricity from both

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[3] Short URL: http://perm.ly/Hertwich_PNAS_2014_Figure1

Permanent URL:

http://public.tableausoftware.com/profile/#!/vizhome/ElectricityTechnologyComparisonsPNAS2014/UnitDashboard thin-film and crystalline PV are lower than those of fossil fuels. Studies assessing thin-film modules have focused on amorphous silicon (63-66) and cadmium telluride (CdTe) (26, 64, 67). Early studies of copper indium gallium selenide (CIGS) cells were based on early production data and module efficiencies that are lower than present values, which resulted in comparatively higher life cycle GHG emissions (64). The results presented in this study indicate that CIGS and CdTe thin-film technologies have lower GHG emissions than reported in previous studies (68); this outcome is partly a reflection of the high capacity factors assumed by IEA. Further, the results show the impact of poly-crystalline silicon PV production in China, where the majority of silicon PV modules are now manufactured. Given the energy intensity of solar-grade silicon production and that electricity production in China is mostly coal-based, higher impacts result from Chinese silicon PV production than European or American manufacturing. The production of PV systems entails a considerable use of materials. Inverters and transformers contribute the most to the high copper use of PV systems. In addition, roof-based systems have high aluminum requirements. As the literature indicates, the availability of critical metals may affect the choice of specific thin-film technologies (69) but is unlikely to hinder the penetration of PV in the foreseeable future, i.e., through 2050 (70).

Given the fast growth of the global PV market and the continued improvement in module performance and materials efficiency, this analysis shows the importance of accounting for technology change and regional origin in terms of environmental impact. Most previous LCA studies have focused on greenhouse gas emissions and energy payback time analysis, with only a limited number quantifying other environmental impacts such as human health impacts, ecotoxicity, and acidification (67, 71, 72). Finally, this analysis is among the first to investigate the change in demand for a broad set of metals used in the PV module (e.g. semiconductor layer), the other components of a PV system, and the entirety of the life cycle of PV electricity. Results show that copper from the inverters and transformers has a significant impact in terms of resource requirements for PV. Due to lack of data, we do not predict any future changes in the material efficiency of transformers and inverters, but future research should investigate possible material efficiency gains from technological advances and economies of scale. It is important to recognize the potential shift in demand for copper as a result of increased PV electricity production. However, production of semiconductor metals for thin-film modules, will likely limit the ability of either CdTe or CIGS to meet the PV demands of the BLUE Map scenario alone. Woodhouse et al. (73) show that current production rates of tellurium and indium will allow a maximum of 9 GW per year of CdTe module production and a maximum of 28 GW per year of CIGS production. Increases in module efficiency and decreases in semiconductor layer thickness in thin films by 2030 and 2050 would allow for larger possible annual production of CdTe and CIGS than estimated by previous assessments. Elshkaki and Graedel (74) indicate that tellurium availability will limit the application of CdTe solar cells, In availability the use of CIGS, and Ag availability the use of silicon-based PV technologies.

Concentrating solar power

CSP with thermal storage can extend electricity production into the late afternoon and early evening peak power demand periods (75). Substantial technical progress (e.g., solar-to-electric energy conversion efficiency) is foreseen especially for central receiver stations (76). This progress may make improved environmental performance feasible in the near future. At this point, significant impacts are connected with producing nitric acid for the heat storage medium, and, in some cases, heat transfer fluid. The production of cement, iron, steel, and glass used in the power plant may also induce significant impacts.

Hydropower

Environmental impacts and benefits of hydropower are more project- and site-specific than those of other technologies. Hydropower plants can have substantial ecological impacts (77, 78) and they contribute to climate change through biogenic methane emissions (79, 80). Reservoir hydropower tends to have a high land use, but land use per unit of energy generated varies by several orders of magnitude depending on geographical factors and storage duration (79). The limited number of available hydropower LCAs does not constitute a representative sample, so we relied on two case studies of reservoir hydropower in our comparison. The global average land use for hydropower is around 100 m^2 per kWh/a electricity generation (80), higher than the case studies investigated here. One of the two reservoir hydropower plants investigated in this study has very low emissions-related indicators and low material requirements. One plant is in a remote area, which increases transport and infrastructure requirements. As a result, the remote project has high material demand, a low net energy gain, and relatively high emissions compared to other renewables. Biogenic GHG emissions per kWh vary with land occupation by many orders of magnitude, with some plants reportedly having higher GHG emissions than coal-fired power plants (79). For the facilities investigated in this study, estimated biogenic emissions were below 1 g CO_2 eq./kWh. Additional studies will be required to understand the likely impacts of the population of future hydropower projects, which will be located mainly in Latin America, Africa and Asia.

Other relevant factors not included in this assessment are biodiversity impacts through habitat change and the obstruction of migration patterns, changes in the amount and composition of sediment swept down the river basin, and social displacement. Such impacts have been considered as individual research subjects for specific cases (81-84) or recommended more generically (85), but there is a lack of methods for addressing these in LCA.

Wind power

Land-based wind power creates few pollution-related impacts on human health and ecosystems. Although offshore wind power projects are more material- and energy-demanding than their land-based counterparts, offshore projects benefit from more favorable wind conditions and a longer assumed lifetime in our analysis (86, 87). Assessed environmental impacts of land-based and offshore systems are usually comparable but somewhat higher for offshore wind. In land-based systems, the production of wind turbine components including spare parts generates approximately 80% of total GHG emissions and 90% of total PM. In offshore systems, roughly one third of environmental impacts are attributable to marine vessel operations and one fifth to production of foundations.

For wind farms situated offshore, array cables within the wind farm, substations and external cables together represent only 4–7% of the total life cycle GHG emissions, but contribute around 30–40% to total impact potentials in the categories of freshwater ecotoxicity and eutrophication. These disproportionately high contributions to toxicity and eutrophication can be largely explained by two factors. The first is the high copper content of submarine cables and substation electrical equipment, and second is long-term leakages of toxic and eutrophying substances from tailings and overburden material deposits in connection with copper mining.

Our LCA of wind power does not incorporate possible effects on bird and bat populations (88) or the growing use of rare earth elements in permanent magnets used in certain direct-drive wind turbines. Supply of rare earth elements is commonly regarded as unreliable (see discussion section below), and their production is reported to cause substantial environmental damage (89-91).

Coal

Coal power generation without CCS has the highest GHG emissions in the energy portfolio. Of the coal power plants we examined, the subcritical coal fired power plant had the largest impact due to its comparatively low efficiency. Coal creates relatively high land impacts, which can be attributed to direct land use of open pit mines and the timber used for the support of underground mines (92). Other life cycle processes, such as the disposal of spoil from coal mining and processing of reclaimed waste from post-combustion capture (93), contribute to freshwater ecotoxicity and eutrophication. As most of the emissions for land use, ecotoxicity and eutrophication are associated with the upstream fuel chain processes, the inclusion of CCS technology and resulting energy efficiency penalty significantly affects the life cycle performance of these impact categories.

Natural gas

Natural gas power generation without CCS has considerably lower GHG emissions than coal-fired power without CCS. However, compared to the renewable technologies discussed in this paper, GHG emissions from NGCC power generation are considerably higher. Natural gas extraction operations contribute more than 90% of total particulate matter formation impacts. NGCC cause very little eutrophication, but its contribution to freshwater ecotoxicity is comparable to that of coal fired power plants.

For natural gas power generation with CCS technology, the inherent energy efficiency penalty amplifies the effect of emissions that occur upstream in the fuel chain process. This effect is large enough to result in life cycle GHG emissions of a natural gas power plant with CCS being comparable to those of coal-fired systems with CCS. The assumed rate of fugitive emissions in the natural gas chain is larger in our assessment than previously assumed due to new evidence on methane emissions from the natural gas system (58, 94). Fugitive natural gas emissions across the supply chain are an important factor in determining life cycle GHG emissions, but the state of the science is not yet conclusive regarding either the magnitude of these emissions or how much they might differ by location and type of gas resource (61, 95). Compared to natural gas power generation without CCS, the energy efficiency penalty is also reflected in the increase of PM formation, eutrophication potential and freshwater ecotoxicity potential.

Because transport of fossil fuels can be an important contributor to overall GHG emissions (96, 97), we conducted a sensitivity analysis in which we tripled the transport distances. This analysis shows that for coal-based technologies, GHG emissions can be increased by up to 7% and particulate matter emissions by up to 23%, while other impact categories are little changed. For natural gas, the relatively small contribution to land use is increased by up to 24%, while the emissions of GHGs are increased by 11% in the case of NGCC with CCS.

Higher increases result when natural gas is transported in a liquefied form (via overseas shipping) instead of pipelines (97).

Critical materials

This study focuses on bulk materials rather than critical metals (98). Among the energy technologies considered in this analysis, critical metals are a particular concern for certain technologies used in wind power, such as neodymium and dysprosium in permanent magnets, and photovoltaic power generation, where indium, gallium, tellurium, and other by-product metals are used as semiconductors. As elaborated in the photovoltaic section above, the functions and services provided by so-called critical metals can potentially be provided by substitutes, which are evaluated by (74, 98). Given the numerous competing uses for metals such as indium, which is used in solder and indium tin oxide coatings used in flat panel displays; gallium, which is used in integrated circuits; laser diodes and light-emitting diodes; and neodymium, which is used in permanent magnets and magnesium alloys, the availability of these metals may constrain specific photovoltaic module or wind power technologies (98). Changes in existing technologies or emerging technologies such as organic polymer, quantum dot and dye-sensitized PV may offer ways to reduce the requirements for critical materials connected to PV. It is too early to make conclusions about the effect of metal criticality on the long-term prospect of a large-scale application of PV. For wind power, the situation is different; if the production of permanent magnets for wind turbines is constrained by dysprosium (Dy) supply (99), wind power can rely on traditional gear box drives, samarium-cobalt magnets, or emerging nano-structured neodymium iron boron permanent magnets (100, 101) that require little or no dysprosium.

Reliability and uncertainty of the results

Our unit results for GHG emissions are mostly within the range of results of the review and harmonization of LCAs conducted by NREL for the IPCC (102-104) and other recent reviews (58, 87, 105). Our results for ground-mounted PV are on the lower end of the range of the literature (106). We think this is the result of two factors: (a) high insolation assumed by the IEA in its scenarios (1), and (b) recent improvements in technology (20). Our results for wind correspond to the median of observations for megawatt-sized wind turbines (87). Differences in GHG emissions between our fossil-fuel based power inventories and results obtained from previous inventory sources (58, 93, 94) are mostly explained by the higher fugitive methane emissions considered in this study. Our study extends the GHG results of the comparison and harmonization project to impacts other than climate change, shows regional variations due to natural conditions, and contains a scenario-based scale-up.

Potential uncertainties about the environmental co-benefits of renewable power compared to fossil power stem from incomplete inventory data. These cut-off errors result from the omission of many small inputs and the omission of pollutant releases in the inventories of some processes (17, 18). Cut-off errors are likely less important for fossil technologies because combustion and fuel production contribute most of the emissions, whereas for renewable technologies, activities occurring in various tiers of complex supply chains are more important. We were able to cover more supply chain activities through the use of economic input-output analysis (16) for selected inputs using a hybrid LCA approach. Data covering all upstream impacts were not available for all technologies.

A major source of uncertainty in our assessment is the fairly favorable assumptions regarding wind conditions, insolation and resulting load factors, the unavailability of regional-specific life cycle inventory data for hydropower, as well as the further development of fossil power plant efficiencies. We took most of these assumptions from the IEA Energy Technology Perspectives (1). Similar assumptions are also found in the LCA literature that formed part of our data source (24). Currently, efficiencies and load factors tend to be lower, resulting in higher emissions intensities and material requirements (87).

Grid balancing

While producing almost one quarter of the electricity in the BLUE Map scenario, solar and wind energy would be responsible for ≤5% of particulate matter exposure, freshwater eutrophication and ecotoxicity resulting from electricity production. However, intermittent renewable sources face challenges in balancing electricity grids and matching demand (107), a factor that is not fully addressed in our study. Extra environmental impacts result from the need to operate fossil fuel or storage hydro power plants to compensate for the variable production from wind and solar technologies (108, 109), the additional grid required to balance supply and demand over larger areas (110), the use of excess renewable capacity that is curtailed in periods of high production (111), and/or energy storage (112). Fripp (108) estimates the spinning and standing reserves of natural gas power required to address the variability of wind power generation assuming a set of wind power plants located in the USA. Reserve requirements reduce dramatically with a better grid due to the averaging of wind conditions across a larger geographic area. Averaging across an area of 500 km in diameter, the impact of operating the reserves are on the order of 25 g CO_2 eq./kWh (108), which is a larger impact than the life cycle impacts of wind power. For variable renewable generation levels similar to the BLUE Map scenario, grid balancing in the NREL Western Wind and Solar Integration Study results in a negligible degradation of CO_2 emissions savings, further reductions of nitrogen oxide emissions, and a degradation of SO_2 emission savings by 2–5% (113). Pehnt et al. (114) investigate the introduction of offshore wind power to the German grid, relying on an electricity market model to investigate the altered operation of other power stations. Pehnt et al. find that depending on the scenario, the additional systems emissions can vary between 18–70 g CO_2 eq./kWh of wind electricity introduced to the system.

In the high wind and solar scenario from the NREL Western Wind and Solar Integration Study as a guide, the need for additional generation from dispatchable reserve power plants to balance variable renewable generation was only 1–3% of the total wind and solar generation in the scenario (113). Furthermore, this study and the BLUE Map scenario do not include any energy storage, but another NREL study (115) shows that for 30–40% variable renewable electricity in the USA, a level higher than BLUE Map, a storage capacity of 1–2% of the total installed capacity of generation could result in significant benefits. Some of this storage capacity would come from existing hydroelectric storage, and some might come from emerging battery or compressed air technologies, for which far less is known about the life cycle impacts. However, the small amount of storage needed, suggests that not including storage will not greatly influence the results of this study.

Third, as variable renewables make up a larger percentage of electricity generation, surplus variable renewable generation must be curtailed at certain times of day and days of the year. This effect was also investigated in (115), which found that approximately 1–3% of variable renewable generation would be curtailed in 2050 under the baseline, 30% and 40% renewable energy scenarios. Those results suggest that the impacts of renewable in the BLUE Map scenario would only be 1–3% higher when considering the effect of curtailment.

Because the BLUE Map scenario relies on moderate amounts (<25%) of variable renewable generation and on fossil fuel generation with CO_2 capture and sequestration, the problem of grid integration is expected to be modest. The challenge of integrating intermittent renewable electricity sources increases with the share of these sources (112, 115), but the life cycle environmental impacts and options for their minimization through employing through more powerful grids, energy storage, flexible demand response, or different forms of back-up are not yet well understood.

IMPLICATIONS FOR FURTHER RESEARCH

A contribution analysis of our results indicates that apart from combustion-related pollution from power stations, mineral and fuel extraction along with processing are the most important causes of environmental impacts. Infrastructure production and transport- or construction-related fuel combustion have smaller but non-negligible contributions. This contribution analysis has important implications for further research:

1. It would be desirable to revisit the environmental impacts of mineral and fuel extraction and processing taking into account the interaction between inventory analysis and impact assessment and addressing the effect of operational practices, regulatory requirements and natural conditions.
2. Manufacturing, transport and construction are often not fully assessed in LCA. LCAs of renewable and nuclear power production, in particular, need to have wide enough system boundaries to appropriately capture these effects. Some of the low GHG emission results reported in the comparison and harmonization studies appear to be an artifact of system boundaries that are too narrow. On the other hand, significant progress has been achieved in recent years and further improvements are in sight, especially for the more novel, renewable technologies, so that earlier assessments are often no longer representative of current technologies.
3. Climate mitigation scenarios often include changes in demand-side technologies to reduce emissions from material production, electricity used for manufacturing, and fuels used for transportation and construction equipment. We included some improvements in these demand-side technologies in our scenario analysis, but a more systematic exploration of potential and expected improvements in material production, manufacturing and transport would be desirable. Neglecting these improvements results in an underestimation of the environmental benefit of climate mitigation. If these measures also require more materials, neglecting the improvements may also result in an underestimation of the total material requirements. We recommend exploring these feedbacks in a sensitivity analysis to determine the proper pathway of addressing the life cycle effects of energy scenarios.

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APPENDIX 1: TABLES

Table S1: The performance improvements of key material production technologies were based on the realistic-optimistic assessment in NEEDS (24), where unit-process level life cycle inventories are provided. The table summarizes energy inputs (electricity and fuels) required by the material production technologies to provide an indication of the technical progress achieved.

Energy inputs, in MJ/kg produced at manufacturing plant	**2010**	**2030**	**2050**
Aluminium	4.5	4.3	4.1
Copper, Europe	8.4	8.2	7.9
Copper, Latin America	10	7.0	6.7
Ferronickel	76	69	66
Nickel	41	39	37
Sinter	1.5	1.3	1.2
Pig iron	14	14	14
Metallurgical grade silicon	45	45	44
Zinc	9.5	6.7	6.3
Clinker	2.6	2.0	1.4
Flat glass	8.5	8.5	7.4

Table S2: Key data for photovoltaics – Assumed energy efficiencies of modules

		Baseline	**2030**	**2050**	**Source**
CIGS	Module efficiency	12%	20.8%	25% (practical limit)	CIGS Roadmap (116)
	CIGS layer	2 µm	1 µm (Ga:In molecular ratio = 2.3)	0.5 µm	CIGS Roadmap (116)
	Mo Back contact	0.65 µm	0.5 µm	0.5 µm	CIGS Roadmap (116)
	Optimize buffer and eliminate emitter layer	Transparent conducting oxide (TCO) (\$2 per m^2)	Optimized TCO (\$1.5 per m^2)	Optimized TCO (\$1.5 per m^2)	CIGS Roadmap (116)
	Glass substrate	3.2 mm glass	2.2 mm anti-reflex glass	2.2 mm anti-reflex glass	CdTe Roadmap (29)
	Capital costs per m^2 module	\$26 per m^2	\$8 per m^2	\$8 per m^2	Author calculation based on CIGS Roadmap (116)
CdTe	Module efficiency	11.6%	18%	24.4% (practical limit)	CdTe Roadmap (29)
	CdTe layer	2.5 µm	1 µm	0.5 µm	CdTe Roadmap (29)
	Optimize buffer and eliminate emitter layer	Zinc oxide (ZnO) (\$2 per m^2)	Optimized ZnO (\$1.5 per m^2)	Optimized ZnO (\$1.5 per m^2)	CdTe Roadmap (29)
Poly-Si	Module efficiency	16%	21%	21%	Wafer Silicon Roadmap (33)
	Poly-silicon wafer thickness	180 µm	120 µm	120 µm	Wafer Silicon Roadmap (33)
	Materials efficient ingot production	900 kg Solar grade silicon (SOG) per ingot	513 kg SOG per ingot	513 kg SOG per ingot	ecoinvent database (3)

Table S3. Key data for parabolic trough and power tower CSP plants (40, 41)

	Trough	**Tower**	**Units**
Gross capacity	118	115	MW
Parasitics (at design point)	15	9	MW
Net capacity	103	106	MW
Annual generation	427	378	GWh/yr
Capacity factor	0.47	0.42	-
Annual grid electricity consumption	3700	7920	MWh/yr
Annual natural gas consumption[a]	8900	0	MMBtu/yr
Total land area	4.1	6.3	km^2

[a] A natural gas-fueled auxiliary boiler is assumed in the trough case and an electric auxiliary boiler in the tower case.

Table S4: Key data for conceptual land-based and offshore wind farms

	Land-based	**Offshore**
Nominal capacity wind farm	150 MW	350 MW
Nominal capacity wind turbine	2.5 MW	5 MW
Lifetime	20 years	25 years
Internal cabling, length	48 km	63 km
No. of transformer stations	1	2
Grid connection length, submarine		50 km
Grid connection length, underground	15 km	10 km
Grid connection length, overhead	15 km	10 km
Land use	0.4 km^2	0.0016 km^2 (benthos)

Table S5: Key data for fossil fuel plants – Power plant efficiencies over time

Power plant efficiency in %	**2010**	**2030**	**2050**
Coal – subcritical without CCS	38.2	-	-
Coal – subcritical with CCS	27.2	-	-
Coal – supercritical without CCS	40.7	49	50
Coal – supercritical with CCS	29.4	39	41
Coal – IGCC without CCS	43.6	49	51
Coal – IGCC with CCS	32.3	44	46
Gas – NGCC without CCS	55.6	64	65
Gas – NGCC with CCS	47.4	55	58

Table S6: Indicator results for various impact categories (measured per unit of kWh electricity delivered) for a larger set of midpoint indicators following the Recipe 1.08 method (6). Impact categories: in bold (A.–E.) impact categories on Figure 1, four additional impact categories are shown in the table but not in Figure 1. The results presented are for the following regions. Fossil fuel powered technologies–China; PV-technologies–OECD North America; Wind power–OECD Europe; Hydropower–Latin America; CSP technologies–Africa and Middle East

Impact category*	**Unit**	**Subcritical wo CCS**	**IGCC wo CCS**	**SCPC wo CCS**	**Subcritical w CCS**	**IGCC w CCS**	**SCPC w CCS**	**NGCC wo CCS**	**NGCC w CCS**
A. Greenhouse gases	kg CO_2 eq.	9.33E-01	7.91E-01	8.71E-01	2.63E-01	2.01E-01	2.36E-01	5.27E-01	2.47E-01
B. Particulate matter	kg PM_{10} eq.	3.35E-04	1.83E-04	3.15E-04	3.81E-04	2.27E-04	4.18E-04	7.57E-04	9.16E-04
C. Ecotoxicity	kg 1,4-DCB eq.	9.60E-03	7.98E-03	8.94E-03	1.49E-02	1.09E-02	1.36E-02	6.31E-03	8.12E-03
D. Eutrophication	kg P eq.	4.82E-04	4.27E-04	4.53E-04	6.87E-04	5.77E-04	6.32E-04	5.40E-06	1.01E-05
E. Land occupation	m^2a	2.04E-02	1.77E-02	1.91E-02	2.91E-02	2.38E-02	2.68E-02	4.88E-04	6.75E-04
Human toxicity	kg 1,4-DCB eq.	1,11E-01	9,11E-02	1,04E-01	1,72E-01	1,25E-01	1,58E-01	8,80E-02	1,12E-01
Metal depletion	kg Fe eq.	9.90E-04	4.92E-04	9.29E-04	1.99E-03	7.75E-04	1.88E-03	2.56E-04	5.21E-04
Photochemical oxidation	kg NMVOC	8.09E-04	6.65E-04	7.62E-04	1.16E-03	8.33E-04	1.06E-03	6.17E-04	7.68E-04
Terrestrial acidification	kg SO_2 eq.	1.10E-03	7.20E-04	1.05E-03	1.23E-03	9.27E-04	1.61E-03	3.78E-03	4.68E-03

Impact category*	**Unit**	**Poly-Si ground**	**Poly-Si roof**	**CIGS ground**	**CIGS roof**	**CdTe ground**	**CdTe roof**	**CSP-Trough**	**CSP-Tower**	**Reservoir 1**	**Reservoir 2**	**Wind onshore**	**Wind offshore steel**	**Wind offshore gravity-based**
A. Greenhouse gases	kg CO_2 eq.	5.70E-02	5.75E-02	1.95E-02	2.43E-02	1.61E-02	2.06E-02	2.27E-02	3.30E-02	7.88E-02	5.59E-03	8.37E-03	1.14E-02	1.11E-02
B. Particulate matter	kg PM_{10} eq.	1.21E-04	1.23E-04	3.59E-05	4.10E-05	3.63E-05	4.13E-05	3.60E-05	6.00E-05	2.06E-04	2.02E-05	2.69E-05	3.96E-05	4.80E-05
C. Ecotoxicity	kg 1,4-DCB eq.	3.18E-03	3.68E-03	5.19E-04	6.87E-04	5.03E-04	6.61E-04	1.22E-04	3.81E-04	1.95E-04	1.80E-05	3.30E-04	3.81E-04	4.27E-04
D. Eutrophication	kg P eq.	3.60E-05	4.45E-05	1.59E-05	1.94E-05	1.41E-05	1.73E-05	4.07E-06	1.40E-05	3.82E-06	3.06E-07	5.86E-06	8.32E-06	8.62E-06
E. Land occupation	m^2a	9.92E-03	1.75E-03	9.71E-03	5.92E-04	1.00E-02	6.06E-04	9.00E-03	1.40E-02	4.44E-03	2.62E-02	2.61E-04	2.96E-04	3.01E-04
Human toxicity	kg 1,4-DCB eq.	6.40E-02	8.14E-02	2.43E-02	2.93E-02	2.29E-02	2.74E-02	5.82E-03	1.26E-02	8.02E-03	6.20E-04	1.15E-02	1.70E-02	1.75E-02
Metal depletion	kg Fe eq.	1.80E-02	1.30E-02	1.66E-02	8.93E-03	1.58E-02	7.88E-03	8.21E-03	1.51E-02	4.44E-03	4.49E-04	1.16E-02	1.15E-02	1.50E-02
Photochemical oxidation	kg NMVOC	1.86E-04	1.93E-04	7.38E-05	8.59E-05	5.62E-05	6.72E-05	8.16E-05	1.47E-04	7.78E-04	5.48E-05	3.19E-05	6.17E-05	8.63E-05
Terrestrial acidification	kg SO_2 eq.	4.22E-04	4.50E-04	1.20E-04	1.51E-04	9.78E-05	1.28E-04	9.96E-05	1.79E-04	4.45E-04	3.32E-05	3.59E-05	7.23E-05	8.81E-05

APPENDIX 2: FIGURES

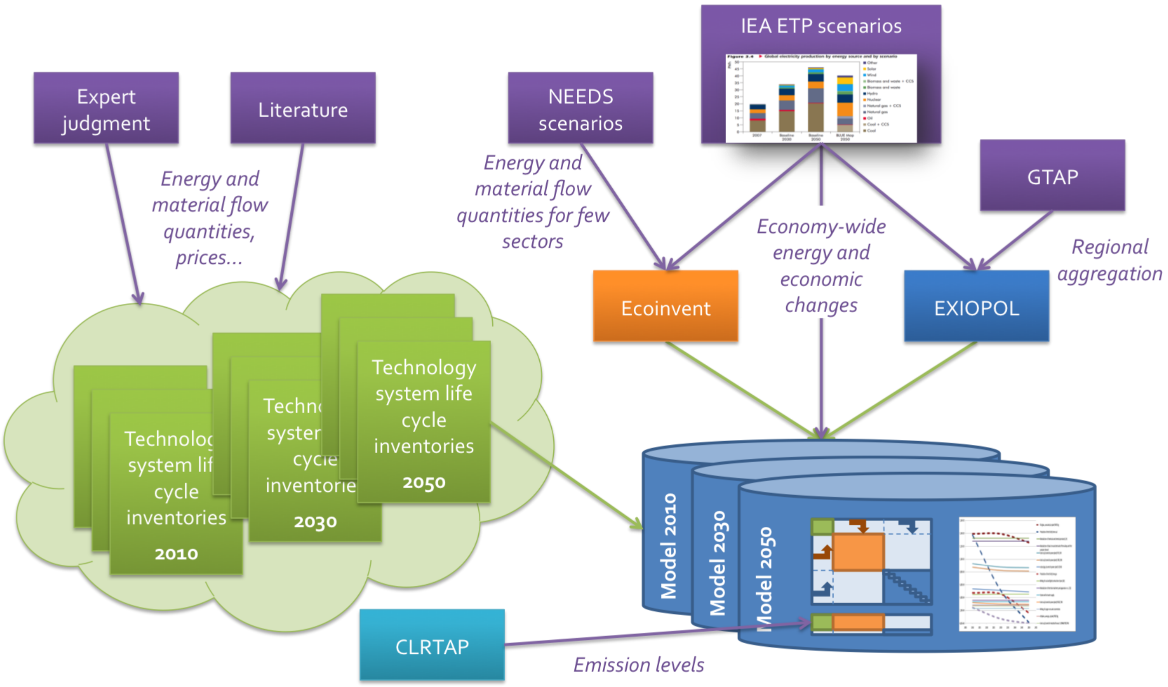

Figure S1: Flowchart of the different flows of information and data in the model. Green arrows represent base data; purple arrows represent external information that modifies these base data. NEEDS–New Energy Externalities Development for Sustainability. IEA ETP–International Energy Agency's Energy Technology Perspectives scenarios, GTAP–Global Trade Analysis Project, EXIOPOL–Externality data and Input-Output tools for POLicy analysis, CLRTAP–Convention on Long-Range Transboundary Air Pollutants. Adapted from (117), with permission from Elsevier.

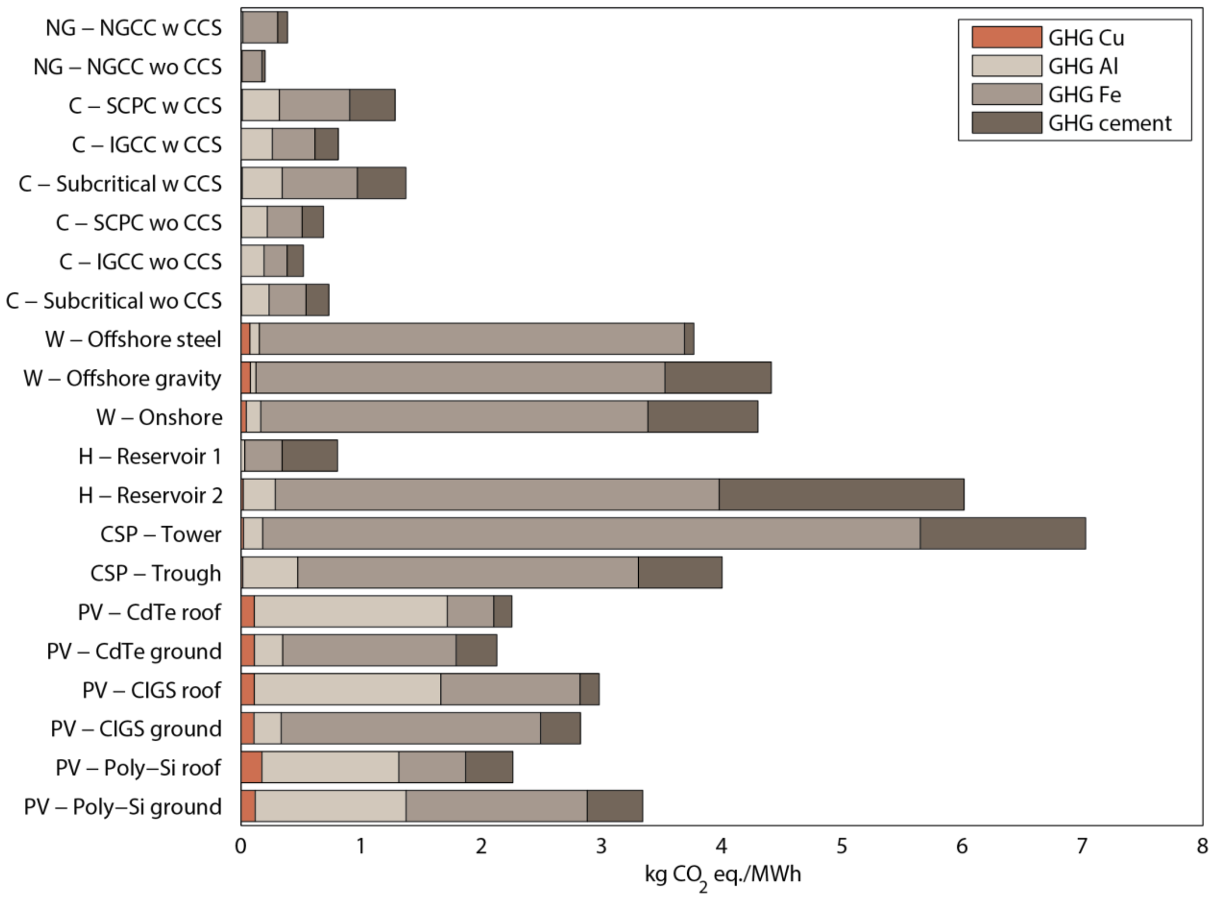

Figure S2: GHG emissions associated with the production of bulk materials for each of the investigated technologies. Abbreviations: PV–photovoltaics, CSP–concentrating solar power, H–hydropower, W–wind power, C–coal, NG–natural gas, Poly-Si–polycrystalline silicon, CIGS–copper indium gallium selenide, Reservoir 1–type of hydropower reservoir used as a lower estimate, Reservoir 2–type of hydropower reservoir used as a higher estimate, Offshore steel–offshore wind power with steel-based foundation, offshore gravity–offshore wind power with gravity-based foundation, CCS–CO_2 capture and storage, IGCC–integrated gasification combined cycle coal-fired power plant, SCPC–supercritical pulverized coal-fired power plant, NGCC–natural gas combined cycle power plant.

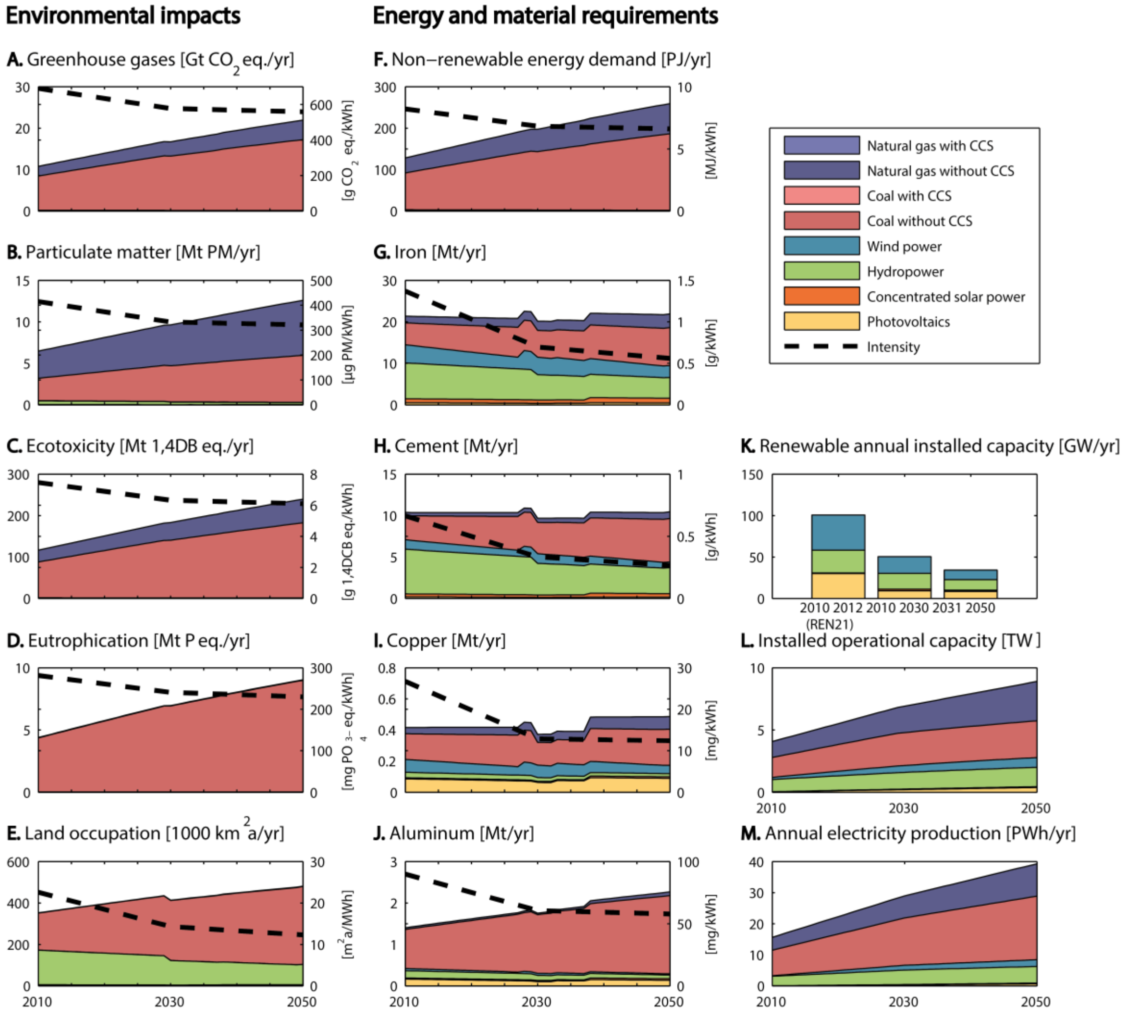

Figure S3: Midpoint indicators, energy and material requirements, absolute, for the IEA baseline scenario. Left: greenhouse gas, particulate matter, freshwater ecotoxicity and eutrophication, and land use. Middle: non-renewable cumulative energy demand, iron, cement, copper and aluminum requirements. Right: average annual capacity growth compared to actual capacity growth 2010–2012 (36), annual installed capacity and electricity production.

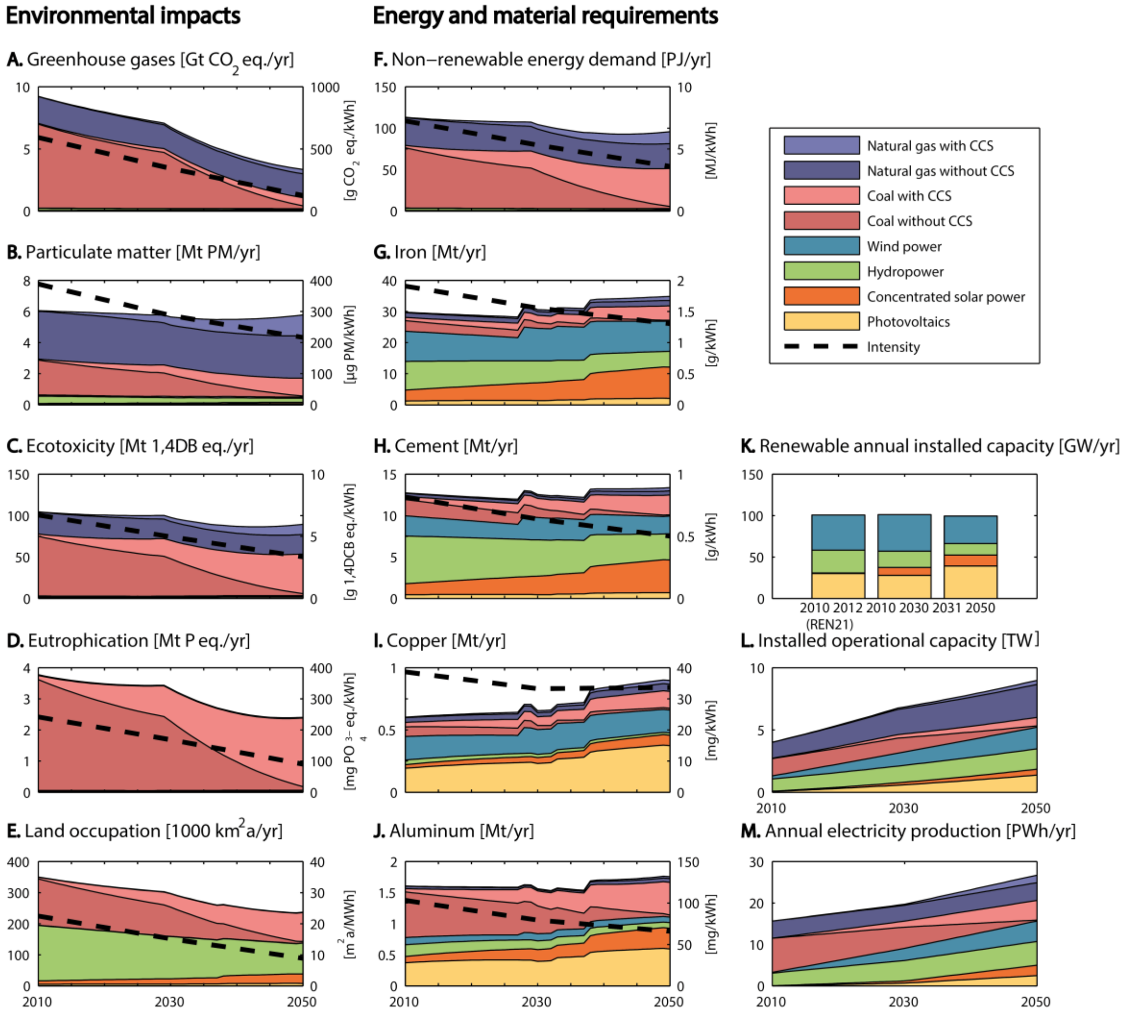

Figure S4: Midpoint indicators, energy and material requirements, absolute, for the IEA BLUE Map scenario. Left: greenhouse gas, particulate matter, freshwater ecotoxicity and eutrophication, and land use. Middle: non-renewable cumulative energy demand, iron, cement, copper and aluminum requirements. Right: average annual capacity growth compared to actual capacity growth 2010–2012 (36), annual installed capacity and electricity production.