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Environmental impacts of high penetration renewable energy scenarios for Europe

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Abstract

The prospect of irreversible environmental alterations and an increasingly volatile climate pressurises societies to reduce greenhouse gas emissions, thereby mitigating climate change impacts. As global electricity demand continues to grow, particularly if considering a future with increased electrification of heat and transport sectors, the imperative to decarbonise our electricity supply becomes more urgent. This letter implements outputs of a detailed power system optimisation model into a prospective life cycle analysis framework in order to present a life cycle analysis of 44 electricity scenarios for Europe in 2050, including analyses of systems based largely on low-carbon fossil energy options (natural gas, and coal with carbon capture and storage (CCS)) as well as systems with high shares of variable renewable energy (VRE) (wind and solar). VRE curtailments and impacts caused by extra energy storage and transmission capabilities necessary in systems based on VRE are taken into account. The results show that systems based largely on VRE perform much better regarding climate change and other impact categories than the investigated systems based on fossil fuels. The climate change impacts from Europe for the year 2050 in a scenario using primarily natural gas are 1400 Tg CO_2-eq while in a scenario using mostly coal with CCS the impacts are 480 Tg CO_2-eq. Systems based on renewables with an even mix of wind and solar capacity generate impacts of 120–140 Tg CO_2-eq. Impacts arising as a result of wind and solar variability do not significantly compromise the climate benefits of utilising these energy resources. VRE systems require more infrastructure leading to much larger mineral resource depletion impacts than fossil fuel systems, and greater land occupation impacts than systems based on natural gas. Emissions and resource requirements from wind power are smaller than from solar power.

1. Introduction

The provision of electricity has become an indispensable part of our society. Countless human activities are founded upon a reliable, abundant and affordable electricity supply. Today's electricity system still uses fossil fuels for the majority of power generation [1]. As a result, the electricity sector causes significant contributions to greenhouse gas (GHG) emissions. For instance, 27% of GHG emissions in EU-27 in 2012 came from the electricity sector [2]. In the coming years the electricity sector is expected to shoulder the majority of energy-related GHG emission reductions,

while potentially undergoing increases in demand if we see large scale electrification of the heat and transport sectors [3]. In its roadmap for a competitive low carbon economy, the European Commission projects almost zero GHG emissions from the power sector by 2050 [4]. As renewable sources displace fossil fuels in the generation portfolio, the magnitude and types of impacts will change. Impacts from electricity are not limited to GHGs; various studies have demonstrated the other environmental burdens caused by the electricity sector, such as resource depletion, human health impacts, and land occupation [5–8]. Quantifying the impacts of a changing

generation mix, including direct effects (e.g. power plant emissions) and indirect effects (e.g. emissions from fuel extraction, infrastructure creation), requires a life cycle approach. Numerous life cycle assessment (LCA) studies exist examining environmental impacts of particular parts of the electricity system, including electricity generation technologies (e.g., [9–12], or literature reviews [13, 14]) and electricity transmission or distribution infrastructure [15–18]. Relatively few studies have attempted to analyse the electricity system as a whole [5, 6, 19], and to our knowledge no LCA studies of electricity systems have taken into account the impacts of energy storage and grid extensions in scenarios with high penetrations of variable renewable energy (VRE).

The present study uses an integrated, hybrid LCA modelling framework [20] to examine 44 different scenarios for the provision of electricity in Europe in the year 2050, explicitly considering additional requirements to accommodate the variability of wind and solar power. The LCA model incorporates the effects of a changing electricity generation mix on electricity inputs to production processes. In this way feedback effects of a cleaner electricity mix are included. The 44 scenarios of European power supply structures in the year 2050 are generated by REMix, a high resolution energy system optimisation model [21, 22]. Among the numerous models that have been used to analyse power systems incorporating large amounts of VRE sources [23, 24], REMix is particularly suitable for the present analysis due to its explicit description of energy storage technologies and transmission grid extensions required in each scenario, in addition to its detailed geographical resolution covering the whole of Europe.

2. Models and scenarios

2.1. Technology hybridized environmental-economic model with integrated scenarios (THEMIS)

THEMIS is a multi-regional, integrated hybrid LCA modelling framework [20]. The current version of THEMIS makes use of the LCA database Ecoinvent [25] and the multi-regional input–output database EXIOBASE [26]. Further, it incorporates prospective life cycle inventory (LCI) data for electricity generation technologies, and integrates these data into all life cycle supply chain descriptions in the model, following either a baseline or a climate change mitigation scenario. In addition to changes in electricity supply, the model includes projected changes in key parameters of industrial production, such as reduced energy inputs to clinker production.

THEMIS has been used previously in analysis of power generation technologies [6]. LCI data for energy storage and transmission technologies are added in the present study, as is described in

section 3. In this study, expected technology for Europe for the year 2050 in a climate change mitigation scenario [20] is used. Environmental impacts for six impact categories are examined using the ReCiPe impact assessment method [27]: climate change, particulate matter formation, freshwater ecotoxicity, freshwater eutrophication, land occupation and mineral resource depletion.
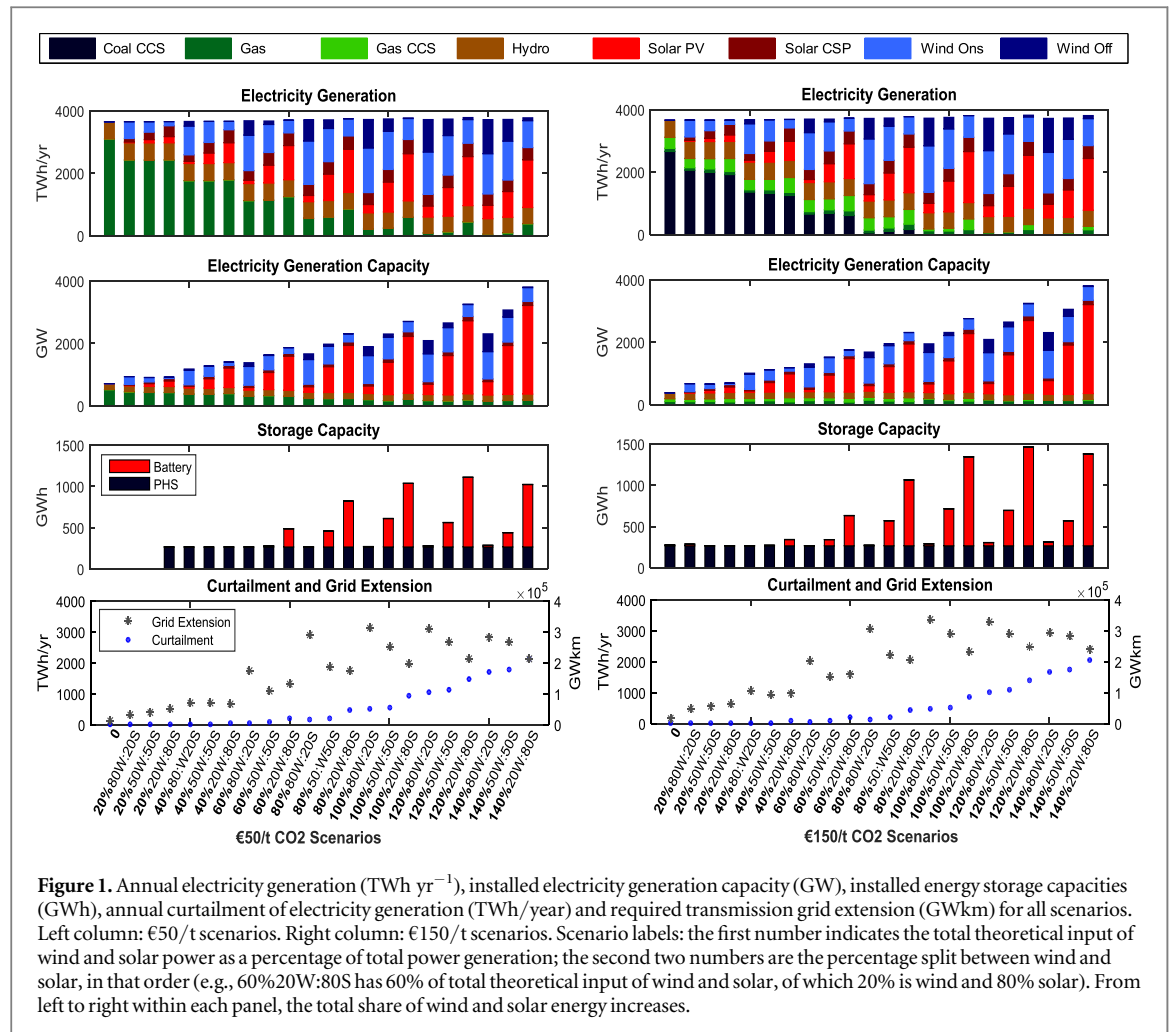
2.2. REMix

REMix is a least-cost energy system optimisation model that determines installed capacities of power generation, transmission and storage units and simulates the operation of these system components [21, 22]. For the present study, the model was parameterised with projections of electricity demand and technical and economic parameters for power generation, transmission and storage technologies for the year 2050 [28, 29]. Investment costs are assumed to decrease due to future technical change in accordance with typical learning rates of large-scale integrated assessment models [29].

Total input of VRE (before curtailment), corresponding share of solar and wind production and the CO_2 price are further input parameters. The input of VRE varies from 0% to 140%. Input can exceed 100% because of curtailment effects, which prevent the total electricity generated from being used. Thus, after curtailment, actual input of VRE to electricity production is always less than 100%. The following VRE splits are explored for each VRE penetration level: 80% wind 20% solar, 50% wind 50% solar, and 20% wind 80% solar. The VRE technologies considered in the REMix assessment are concentrating solar power, roof-mounted and ground-mounted solar photovoltaic (PV), as well as onshore and offshore wind power. Potentials for each technology are quantified in [22]. Residual electricity production is determined by economic optimisation. The costs to be minimised are the total system costs, i.e. the sum of all investment, fixed and variable operation costs.

Results are presented here for scenarios with two CO_2 prices, €50/t and €150/t. These values represent 2050 price levels that deliver significant degrees of climate change mitigation in mitigation scenario literature. The €150/t price is roughly consistent with the 2050 carbon price of the most ambitious reference mitigation scenario (the 'RCP2.6') considered by the IPCC Fifth Assessment Report [30, 31]. In €50/t scenarios the model selects natural gas combined cycle without carbon capture and storage (CCS) as the baseload technology, while in €150/t scenarios coal with CCS is selected. Notably, there is no input from nuclear, biomass or coal without CCS in any scenario. This is not a conscious modelling decision but rather an outcome of the model.

Three storage technologies are considered in REMix: pumped hydro storage (PHS), battery storage

Figure 1. Annual electricity generation (TWh yr^{-1}), installed electricity generation capacity (GW), installed energy storage capacities (GWh), annual curtailment of electricity generation (TWh/year) and required transmission grid extension (GWkm) for all scenarios. Left column: €50/t scenarios. Right column: €150/t scenarios. Scenario labels: the first number indicates the total theoretical input of wind and solar power as a percentage of total power generation; the second two numbers are the percentage split between wind and solar, in that order (e.g., 60%20W:80S has 60% of total theoretical input of wind and solar, of which 20% is wind and 80% solar). From left to right within each panel, the total share of wind and solar energy increases.

and hydrogen storage. While other technologies for storing energy exist, the three just-mentioned options are assumed to be overall representative in terms of main technical and economic characteristics. Load shifting measures are not considered in this work, but could further reduce the system costs and replace storage to some extent [32]. The scenarios presented here show zero utilisation of hydrogen storage. The representation of power transmission is in this study limited to DC links between neighbouring countries.

2.3. Combined model
The environmental performance of the electricity systems described by each REMix scenario, incorporating electricity generation mixes, energy storage capacity creation and utilisation, and transmission grid extensions, are analysed using THEMIS. Technological characteristics (i.e. inputs and emissions of each technology at each life cycle stage) of the required technologies are defined in THEMIS. Expected technology for Europe in 2050 is used, including expected power plant technologies and efficiencies. For example, electricity generation from coal is provided by a mix of technologies (integrated gasification combined cycle, supercritical generation and subcritical generation) which is more developed than today. Similarly, the

electricity generation from solar PV is provided by a mix of PV types (polycrystalline silicon, cadmium telluride and copper indium gallium selenide), and in addition a distinction is made between ground-mounted (about 40% of total) and rooftop installations (60%). All such assumptions about specific breakdowns of electricity generation technologies are adopted from [6], and are shown in table S1.

2.4. Scenarios
The REMix scenarios described above total 22 for each CO$_2$ price. Figure 1 summarises results for all scenarios. Scenarios based on VRE have considerably larger installed capacities than scenarios based on conventional thermal generation. This is more pronounced for solar power than wind power, because of the smaller capacity factors for solar power. There is a constant capacity of PHS in almost all scenarios, and large creation of battery storage capacity in scenarios with high solar production. Hydrogen storage is not visible as this technology is never invested in by REMix in these scenarios. Curtailment levels rise with increasing penetration of VRE, becoming a significant proportion of total generation. Grid extensions also increase with higher input of renewables, especially wind. Transmission losses vary by scenario within the

Table 1. Input coefficients for HVDC lines and cables to 1 GWkm grid extension.

Component	Data source	Capacity (GW)	Percentage input to extensions	Lifetime (years)	Input to 1 GW km
Overhead line	[40]	0.5	20%	40	0.01
Land cable	[43]	0.6	5%	40	0.002
Sea cable	[44, 45]	0.7	75%	40	0.027

range of 0.1%–2% of total generation (note that this only includes losses in DC connections between countries; other transmission losses are not considered). The scenarios are labelled as follows: the first number indicates the total theoretical input of VRE as a percentage of total generation; the second two numbers are the percentage split between wind and solar, in that order. So, scenario 60%20W:80S has 60% of total theoretical input of VRE; 20% of that is from wind and 80% from solar.

3. LCI data

Life cycle inventories are presented for grid infrastructure and storage technologies added to the model for this study. Electricity generation processes already existing in THEMIS are described in supplementary information to [6] and [20]. Table S1 in the supporting information provides an overview of all individual technologies modelled in THEMIS for this study.

3.1. Energy storage
In the present study, installed capacities for each storage technology (PHS and battery) and aggregate stored energy amounts (combined PHS and battery) are obtained from REMix, and further it is assumed that the amount of energy storage performed by each technology is proportional to the installed capacity of the technology. The following subsections describe the LCI data for energy storage technologies.

3.1.1. Battery
Material inputs and emissions for battery storage are adapted from a study of Li-ion battery packs for use in electric vehicles [33]. Sodium-sulfur (NaS) batteries may be a superior technological solution for grid scale storage [34, 35], but LCI data are not currently available. Li-ion technology is not without its merits, including high energy density and high efficiencies [34]. Adaptations of the source data for use in this study involve removal of battery tray and battery retention, which are only needed for vehicle installation. After the adaptations, the 220 kg battery pack provides an energy storage capacity of 26.6 kWh. The lifetime of the battery is 10 years. Operational impacts for all storage technologies arise solely from extra electricity production to compensate for losses and are determined by the efficiency of the conversion cycle. A round trip efficiency of 90% is assumed for battery storage [36].

3.1.2. Pumped hydro
Following the approach in Ecoinvent [37], the construction of PHS reservoirs is assumed to be identical to construction of hydroelectric reservoir power plants. Following consideration of a review of biogenic emissions from hydropower and PHS plants [38], biogenic emissions are not considered due to the lack of a proper understanding of the way PHS developments affect biogenic GHG emissions. Round trip efficiency for PHS is 70%.

3.2. Electricity transmission
Inputs to high voltage direct current (HVDC) transmission grid extension encompass HVDC lines and cables, gas insulated substations and AC–DC converter stations. LCI data sources and the approach for incorporating inputs to grid extension are detailed in the following subsections.

3.2.1. Lines and cables
Lines and cables are comprised of overhead lines, land (subterranean) cables and subsea cables. ENTSO-E [39] reports that 75% (of length) of HVDC network extensions in the coming decade will be sea cables, 20% will be overhead lines, and 5% will be land cables. This breakdown is adopted in this study. Material requirements for overhead lines come from a statement by the Danish transmission system operator for a 400 kV overhead DC line [40]. The power transmission capacity of the line is not explicitly mentioned; based on specifications of a 350 kV HVDC line with a capacity of 300 MW [41] and applying an assumption of future technology development, a capacity of 500 MW is assumed. Land occupation figures for overhead lines are added using a conservative assumption of 50 m required ground clearance area, based on figures from [42].

Material requirements for land cables come from a description of the 600 MW connection between Germany and Denmark [43]. Subsea cable data is based on data from the 700 MW NordNed link [44] and utilises material assumptions outlined in [45]. The lifetime of all lines and cables is 40 years. Input coefficients to grid extension for all lines and cables are summarised in table 1.

3.2.2. Electrical equipment
We include analysis of DC to AC converter substations and conventional voltage substations which convert from high voltage to lower voltage, creating the link between the transmission and distribution levels. DC

Table 2. Input coefficients for substations and substation equipment to 1 GWkm grid extension.

Component	Data source	Input to one station	Distance between stations (GWkm)	Lifetime (years)	Input to 1 GWkm
Converter substation	[16]	—	100	70	0.0001
500 MVA transformer	[46]	4/3	—	35	0.0004
250 MVA transformer	[47]	2/3	—	35	0.0002
Voltage substation	[16]	—	100	40	0.0002
Gas insulated switchgear	[49]	10	—	40	0.0025

to AC current converter station equipment data is currently not available, and is approximated with AC power transformer data [46, 47]. Material requirements for the site structure are assumed to be similar to those for a gas insulated substation [16], and are scaled by the expected quantity of concrete in HVDC converter sites [48]. The lifetime of transformers is 35 years [46, 47], and the lifetime of the structure is 70 years (own assumption). It is assumed that there exists one converter station for every 100 GWkm. Taking an average transmission grid capacity of 0.65 GW, that corresponds approximately to one substation for every 150 km of transmission grid.

Voltage substations are assumed to be gas insulated (as opposed to air insulated). Site structural data is from [16] and gas insulated switchgear material and emission data is from an environmental product declaration of gas insulated switchgear [49]. One substation contains 10 bays of switchgear. Equipment lifetime is 40 years and it is assumed there is one substation for every 100 GWkm of grid extension. SF_6 leakages are 22 kg per unit switchgear over the 40 year lifespan, or roughly 0.1% per annum, a suitable upper limit for future leakages [50].

4. Results and discussion

4.1. Overall system impacts
Figure 2 depicts total life cycle impacts for all 44 scenarios in the six impact categories.

4.1.1. Climate change
Climate change impacts reduce considerably with increasing inputs of renewable energy. Lowest impacts for both €50/t and €150/t scenarios are in the 140%80W:20S scenario, where generation comes almost exclusively (99%) from renewables. Increasing VRE input from 0% to 140% with a CO_2 price of €50/t reduces impacts by 78% (140%20W:80S) or 93% (140%80W:20S). Similar increases with a €150/t CO_2 price reduce impacts by 57% or 81%. It is seen that systems with large inputs of solar energy have higher impacts than those with large inputs of wind. The marginal benefit of increasing VRE penetration decreases when moving beyond 100%: Taking €50/t scenarios with a 50:50 wind solar split, impacts are 0.19, 0.15 and 0.14 Pg CO_2-eq in 100%, 120% and 140% scenarios, respectively. Such reductions are less

significant than in 50:50 scenarios with VRE increasing from 60% to 80% and 100%, where impacts are 0.56 Pg CO_2-eq, 0.33 Pg CO_2-eq and 0.19 Pg CO_2-eq respectively.

As for the effects of CO_2 price, impacts in €150/t scenarios are smaller than impacts in €50/t scenarios, largely due to coal power with CCS replacing natural gas power without CCS as baseload technology. The magnitude of impact reductions as input of renewables increases is therefore smaller in €150/t scenarios than in €50/t scenarios, although considerable reductions are still visible, especially in systems dominated by wind power.

4.1.2. Freshwater eutrophication
Eutrophication impacts from coal overshadow impacts from all other technologies. These impacts from coal are primarily caused by leaching of phosphates from landfill disposal of spoil from coal mining. Eutrophication impacts increase as natural gas is displaced by renewables in €50/t scenarios—this is mainly due to leaching of phosphates from tailings produced during processing of copper used in solar and battery storage. These increases are negligible in comparison with impacts from coal, however. Increasing inputs of wind and solar from 0% to 100%–140% in €150/t scenarios reduces impacts by 91%–97%.

4.1.3. Freshwater ecotoxicity
Toxic impacts are closely related to coal and natural gas supply chains, arising from metal pollutants (nickel and magnesium) in ground water from disposed coal mine spoil, pollutants to river water from coal power plants, and emissions (particularly of bromine) to water during natural gas extraction. There are significant impacts from solar PV, due to disposal of sulfidic tailings during copper processing and chlorine emissions to water during silicon refinement. Still, impacts are lowered with increasing input of renewables. The largest reductions are seen in €150/t scenarios, where impacts from a system with high input of wind power (120%80W:20S) show reductions of 92% compared with a system based largely on coal (0% VRE).

4.1.4. Particulate matter formation
Natural gas is the prime cause of particulate matter formation, owing to SO_2 releases during gas
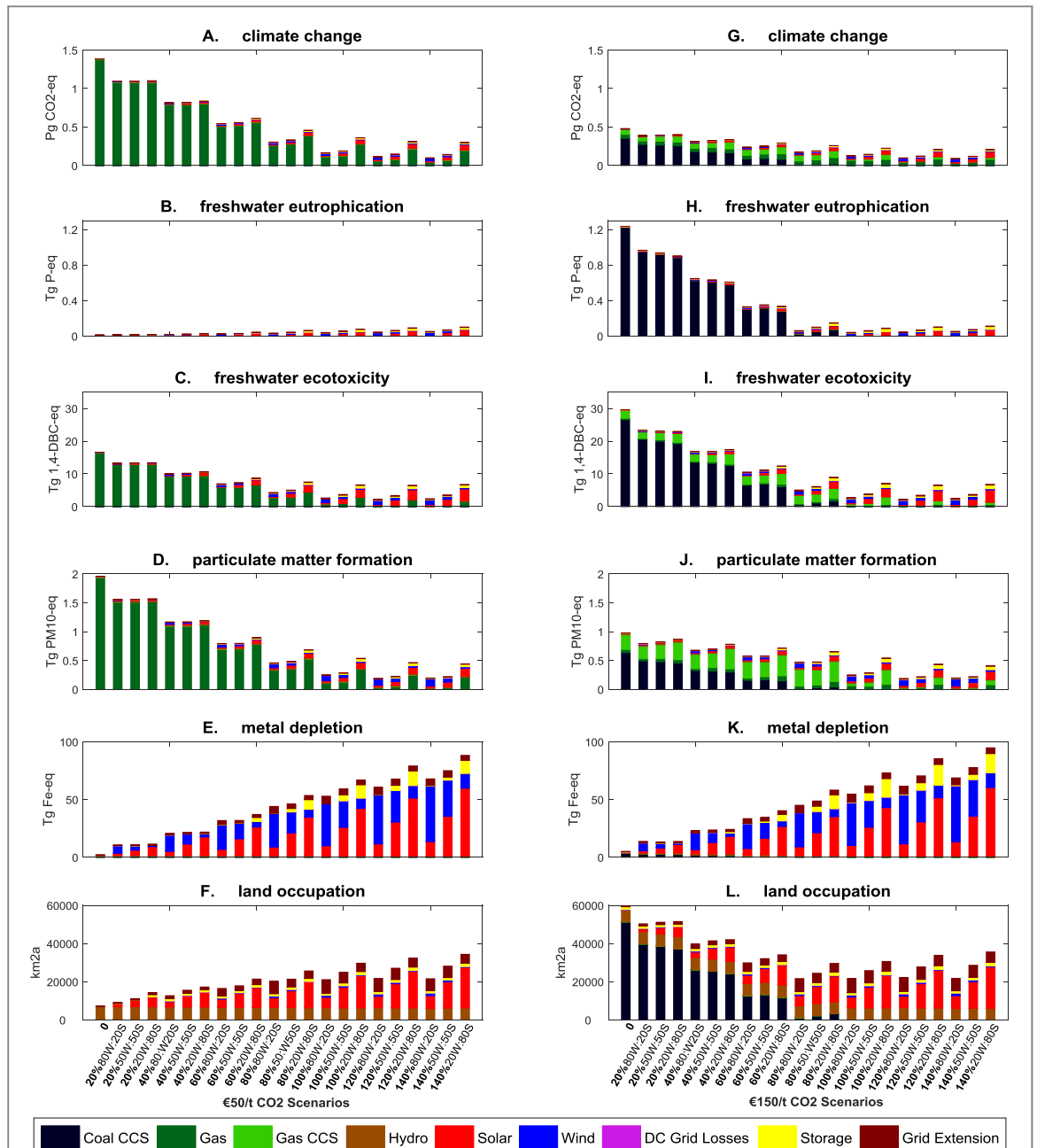
Figure 2. Annual environmental impacts for all scenarios, broken down into contributions from various power generation technologies, DC grid losses, energy storage and DC transmission grid extensions. Left column: €50/t scenarios. Right column: €150/t scenarios. Scenario labels: the first number indicates the total theoretical input of wind and solar power as a percentage of total power generation; the second two numbers are the percentage split between wind and solar, in that order (e.g., 60%20W:80S has 60% of total theoretical input of wind and solar, of which 20% is wind and 80% solar). From left to right within each panel, the total share of wind and solar energy increases.

extraction. Impacts from coal are smaller but still considerable, and arise from tailpipe emissions after combustion as well as emissions during blasting at hard coal mines. Impacts are therefore higher in scenarios with high input of fossil fuels (particularly natural gas), and lower as input of renewables increases. Scenarios with lowest impact are those with high inputs of wind. The CO_2 price makes little difference to impacts in scenarios with high renewable input. Solar PV production causes notable emissions; this is attributable to production of metallurgical grade silicon.

4.1.5. Mineral resource depletion
Mineral resource depletion is the only examined category in which impacts consistently increase with increasing input of VRE. Figures 2(E) and (K) show that impacts arise mainly from creation of wind and solar capacity, although some impacts results from energy storage and grid extensions. Manganese and copper, followed by iron, nickel and chromium, are resources which lead to high depletion impacts. Comparing a system based on natural gas (0% VRE, €50/t CO_2) with a system based almost entirely on

renewables (140%50W:50S, €50/t CO_2), impacts increase by a factor of 36 from 2.1 to 75 Pg Fe-eq.

4.1.6. Land occupation

Coal is the most intensive electricity technology regarding land occupation, due to timber requirements in coal mines as well as dumping and extraction at the mining site. Ground mounted solar systems also cause large impacts. Comparing a system largely based on natural gas (0% VRE) with a predominantly renewable system in €50/t scenarios, factor 3.0 (140% 80W:20S) or 4.7 (140%20W:80S) increases in land occupation are visible. The corresponding comparison with a €150/t CO_2 price between a system based on coal with CCS (0% VRE) and a largely renewables based system results in reductions of 63% (140% 80W:20S) or 40% (140%20W:80S) in land occupation. Thus the effect of increased renewables on land occupation depends on which kind of system you transition from. It is worth noting that the direct land use of wind farms is measured as the area occupied by wind turbines and other infrastructure, excluding the land between infrastructure elements, as the wind farm does not prevent this land from fulfilling other functions such as agriculture [6].

4.2. Impacts of grid extension, storage and losses

The combined impacts of DC grid extensions, energy storage and losses for scenarios with a €150/t CO_2 price are shown in figure 3. Corresponding figures for €50/t CO_2 price scenarios are broadly similar. The figures are arranged according to theoretical input of wind and solar to the electricity mix, so for example the bottom left point shows the 0% renewable scenario, and the top-most point shows the 140% 20W:80S scenario, corresponding to 28% (20%·140% = 28%) theoretical input of wind and 112% (80%·140% = 112%) theoretical input of solar. The rationale for presenting this figure is to show the influence of deployment of wind and solar on impacts from grid extension, storage and losses, and further to show how these impacts vary depending on source of VRE (i.e., the split between wind and solar). Impacts of curtailment are not considered here, owing to relatively small variations in curtailment depending on wind-solar splits (see figure 1), and difficulty in determining consistent estimates of impacts associated with curtailment.

It is seen from figure 3 that for all impact categories excepting land occupation, solar power leads to higher impacts from grid extension, storage and losses. For example, climate change impacts in scenario 140% 80W:20S are approximately 5 Tg CO_2-eq, whereas impacts in scenario 140%20W:80S are around 20 Tg CO_2-eq. The magnitude of the difference in impacts varies for different scenarios and impacts categories. An exception to the norm is land occupation, where due to larger grid extensions being required for wind

power, marginally higher impacts occur in high wind scenarios than in high solar scenarios. In general for the results depicted in figure 3, impacts from storage and grid extension are dominant, while impacts from power losses are negligible.
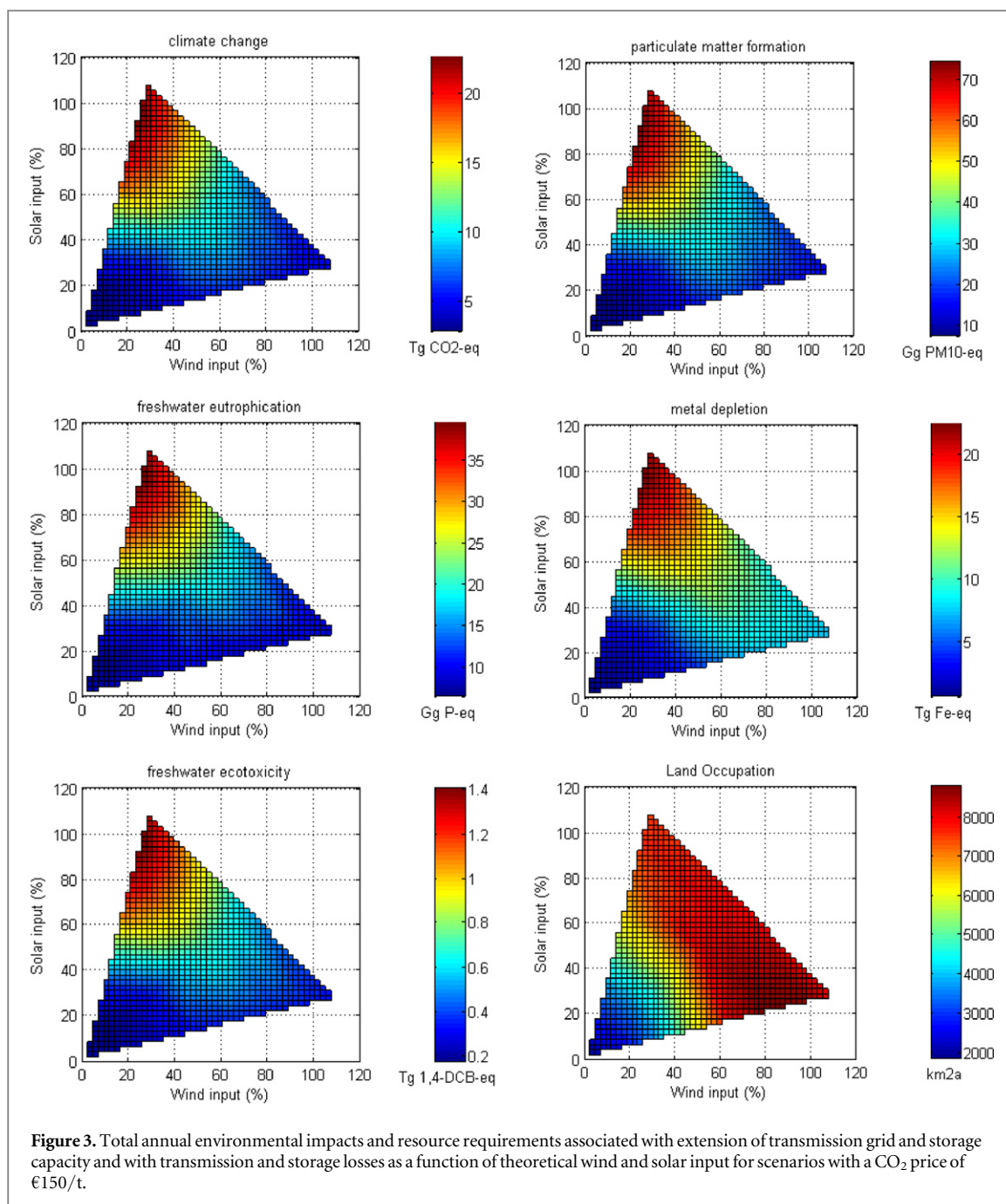
4.3. Summary of results

The main findings of the analysis are as follows: (i) increased penetration of wind and solar leads to large reductions in climate change impacts and co-benefits in most other impact categories, excluding mineral resource depletion and in some cases land occupation. (ii) The additional impacts that arise as a result of the variability of wind and solar energy do not significantly compromise their climate benefits. (iii) Activities related to extraction of fossil fuels, particularly methane and sulfur dioxide releases during natural gas extraction and disposal of spoil from coal mining, are significant polluting processes in many impact categories. (iv) Copper is a prime cause of impacts in a number of impact categories. Disposal of tailings from copper benefication causes toxic and eutrophying emissions, and copper mining contributes significantly to mineral resource depletion. (v) The impacts of grid extension and energy storage are relatively minor except in the case of mineral resource depletion and to a lesser extent land occupation. (vi) Solar power is found to induce consistently larger impacts than wind power; this is due to both higher impact intensity for solar power and greater need for storage caused by solar's lower capacity factors.

4.4. Comparison with existing literature

Results that are in some ways similar to present results have been found in the small body of literature analysing impacts of electricity systems without consideration of additional impacts due to the variable nature of wind and solar energy [5, 6, 19]. The benefits of renewable energy sources in reducing GHG emissions is a common finding across studies, and still holds in this study after inclusion of grid extension and energy storage requirements. In this respect, the current study may be regarded as confirming the climate benefits of replacing fossil power with wind and solar power. The climate change impacts per kWh found in 60% VRE scenarios with a €50/t CO_2 price, 0.146–0.163 kg CO_2-eq, are comparable to the 0.168 kg CO_2-eq reported for the 2030-Green scenario with 60% wind input reported by Turconi *et al* [19]. Impacts in 60% VRE scenarios with a €150/t CO_2 price are considerably lower, 0.064–0.077 kg CO_2-eq. Much smaller impacts of 0.02 kg CO_2-eq are reported by Kouloumpis *et al* [5] in a scenario (B4) which uses approximately 60% renewable energy and 40% nuclear power and does not consider impacts arising from storage or transmission. Other common results across studies are that the transition to a low carbon electricity system invariably leads to greater material

Figure 3. Total annual environmental impacts and resource requirements associated with extension of transmission grid and storage capacity and with transmission and storage losses as a function of theoretical wind and solar input for scenarios with a CO_2 price of €150/t.

requirements, especially if that system relies mostly on renewable energy [6, 45, 51], and that replacement of traditional fossil fuel plants by their equivalent with CCS offers significantly less environmental benefits than replacement by renewables [6].

Aside from the inclusion of storage and grid extension impacts in this study, some notable differences exist between this and previous studies. Most notable is perhaps the inclusion of biomass, nuclear and net imports in other studies [5, 19]. The contribution of nuclear to future electricity supply in Europe is uncertain, but unlikely to be zero. Based on current project plans and shut-downs, ENTSO-E predicts a reduction of European nuclear capacity of up to 25 GW by 2030 [39]. Extensive use of biomass for future electricity

generation is also a controversial issue. While there may be energy security benefits and GHG reductions associated with biomass use (assuming that biogenic CO_2 is carbon neutral), biomass can in some cases cause significant environmental impacts regarding climate change, acidification, eutrophication and land use [5, 19]. It would be useful to include nuclear and biomass in future scenarios if they are likely to play a significant role. Regarding imports, as the region of concern in here is Europe, net electricity imports (which would be mostly with Russia, Turkey and potentially North Africa) outside of this region are considered to be of limited magnitude compared with total production in Europe. This may turn out not be the case if Turkey develops its vast potential for

hydropower or if North Africa develops its vast solar potential, and sufficient transmission interconnections are constructed between those regions and the European grid.

5. Conclusions

Future electricity system and energy scenario analyses can benefit from considering the life cycle impacts of technologies. This study represents an attempt to combine life cycle and power system modelling techniques, and is the first such study to examine the whole European region. A further key novelty of this LCA is the incorporation of the effects of renewable energy curtailment and required energy storage and transmission grid extensions. The results show that despite extra impacts being caused by energy storage and grid extensions, their relative magnitude are not large enough to undermine the environmental benefits of switching to renewables and thus the case for switching to renewables based on climate change and other environmental impacts is strengthened. Beyond the energy storage and power transmission options considered in the present work, future research may address the roles of balancing options such as electric vehicles and demand side management in the power system, as well as the environmental impacts arising from their use.

An expanded system analysis would be required to analyse the decarbonisation of the energy system as a whole, addressing important issues such as the technical and material feasibility, and environmental implications, of electrifying the heat and transport sectors while achieving GHG targets.

Acknowledgments

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