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Health benefits, ecological threats of low-carbon electricity

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Supplementary material for this article is available online

Abstract

Stabilizing global temperature will require a shift to renewable or nuclear power from fossil power and the large-scale deployment of CO_2 capture and storage (CCS) for remaining fossil fuel use. Non-climate co-benefits of low-carbon energy technologies, especially reduced mortalities from air pollution and decreased ecosystem damage, have been important arguments for policies to reduce CO_2 emissions. Taking into account a wide range of environmental mechanisms and the complex interactions of the supply chains of different technologies, we conducted the first life cycle assessment of potential human health and ecological impacts of a global low-carbon electricity scenario. Our assessment indicates strong human health benefits of low-carbon electricity. For ecosystem quality, there is a significant trade-off between reduced pollution and climate impacts and potentially significant ecological impacts from land use associated with increased biopower utilization. Other renewables, nuclear power and CCS show clear ecological benefits, so that the climate mitigation scenario with a relatively low share of biopower has lower ecosystem impacts than the baseline scenario. Energy policy can maximize co-benefits by supporting other renewable and nuclear power and developing biomass supply from sources with low biodiversity impact.

Introduction

Documented co-benefits of climate change mitigation can provide a strong rationale to mobilize investments in new power generation and overcome established interests [1–5]. At the same time, identifying potential adverse side-effects of specific strategies serves to target investments and avoid mistakes that may be difficult to reverse given the required speed of phase-out for conventional fossil power [4, 5]. One tool that makes potential co-benefits, side-effects and trade-offs visible is life cycle assessment (LCA) [6]. From the point of view of assessing the implications for climate policy of LCAs of energy technology, there is a shortage of literature analyzing life cycle inventories and presenting the results in a comparative and integrated manner that can be understood by experts from adjacent fields. To be identified as a finding that has a high degree of evidence and confidence in an assessment by the Intergovernmental Panel on Climate Change (IPCC), research findings must be documented in the peer-reviewed literature and a larger body of research needs to exist that points in the same direction. The IPCC specifically recommends that 'a forward-looking life-cycle assessment (LCA) can help to reduce undesired lock-in effects with respect to the construction and operation of large physical infrastructure' [7], where a sub-optimal technology could become engrained and hinder the introduction of more desirable technologies. Reviews and analyses of technologies [8–10] address individual air pollutants under existing conditions; they are a valuable background but lack the forward-looking and integrative perspective and do not provide an assessment of the multiple and aggregate environmental and health impacts of a fundamental

Table 1. Midpoint indicator aggregation, following the ReCiPe 1.11 methodology [14].

Group	Environmental mechanism	Endpoint
Land occupation, transformation	Agricultural land occupation, land transformation potential, urban land occupation potential	Ecosystem quality
Toxicity	Freshwater ecotoxicity potential, human toxicity potential, marine ecotoxicity potential, terrestrial ecotoxicity potential	Human health, Ecosystem quality
Air pollution	Ozone depletion potential, particulate matter formation potential, photo-oxidant formation potential	Human health
Greenhouse gases	Global warming potential	Human health, Ecosystem quality
Eutrophication, acidification	Freshwater eutrophication potential, terrestrial acidification potential	Ecosystem quality
Ionizing radiation	Ionizing radiation potential	Human health

transformation of the energy system [5]. Recently, prospective studies have addressed the life cycle impacts of power generation options for Switzerland [11] and scenarios for the United Arab Emirates [12] and the United Kingdom [13]. Such studies point in a valuable direction of interest to policy makers, and more work in the same vein is needed addressing more broadly applicable situations.

Here, we present comparative LCA results of electricity generation, as foreseen by the baseline and 2 °C mitigation scenarios of the International Energy Agency (IEA) [14], addressing human health and ecosystem quality endpoints based on recent advances in impact assessment to integrate the contribution of many environmental mechanisms to these two endpoints, human health damage measured in disability adjusted life years and ecosystem impact measured in disappeared species (table 1) [15]. Individual technologies and entire generation mixes following the two IEA scenarios are assessed using an integrated hybrid life cycle inventory model to account for impacts associated with the construction, operation and decommissioning of power plants, including the energy mix used at the time of construction [16,17]. In the IEA baseline scenario, global generation capacity increases from 4.5 TW in 2010 to 10 TW in 2050, with 3.1 TW natural gas, 3 TW coal, 1.5 TW hydropower, 0.8 TW wind, and 0.6 TW nuclear. In the mitigation scenario, a diversified portfolio of hydro, wind, solar and nuclear power accounts for 4.3 TW, gas supplies 3 TW, of this 0.3 TW with CCS, coal 0.7 TW mostly with CCS, and biomass and waste contribute 0.4 TW (table 2). The work extends our earlier, comparative analysis of electricity generation options [17], which was less integrative (reporting selected environmental mechanisms, not endpoints) and covered fewer technologies.

The ecosystem quality and human health impacts of hundreds of pollutants, resource flows, and three different land use types were assessed in terms of species-years of biodiversity loss and disability-adjusted life years of human health impact, respectively, using the latest available update of a widely applied set of life cycle impact assessment methods

Table 2. Assumed installed capacity for each technology considered, adapted from [13]. Non-modelled technologies are in italics.

Global capacity installed, GW	Reference	IEA Baseline		IEA BLUE Map	
Year	*2007*	*2030*	*2050*	*2030*	*2050*
Coal	1440	2605	2958	1138	65
Coal w CCS	0	0	0	201	673
Gas	1168	1972	3152	1935	2647
Gas w CCS	0	0	0	39	333
Biomass & waste	46	147	184	282	348
Biomass w CCS	0	0	0	16	50
Oil	*445*	*328*	*188*	*299*	*182*
Nuclear	371	475	610	684	1187
Hydro	923	1362	1556	1391	1635
Ocean	*0*	*3*	*9*	*17*	*49*
Geothermal	*11*	*26*	*42*	*45*	*144*
Solar PV	8	201	378	410	1378
Solar CSP	1	44	72	146	473
Wind onshore	95	522	658	920	1293
Wind offshore	2	81	119	214	444
Total	**4509**	**7765**	**9927**	**7737**	**10901**

[15]. The advantage of this set of methods is that it allows for the quantification of the aggregate effect of air pollution (particulate matter, photo-oxidants, ozone-depleting chemicals), human toxicity, ionizing radiation, and climate change on a common endpoint, human health. Similarly, the impacts of land use, freshwater eutrophication, terrestrial acidification, freshwater, terrestrial and marine ecotoxicity and climate change on ecosystem quality are aggregated in terms of species-years of biodiversity loss. Each method addresses one environmental mechanism by which a pressure, such as a pollutant release or land occupation, leads to a health or ecosystem impact. By combining these environmental mechanisms, the methods reduce the assessment to just two endpoint indicators, for human health and ecosystem quality, which are more easily taken into account in decision making than the wide range of mechanism-specific indicators that are used in life cycle assessment at a midpoint level. While there is more uncertainty about the contribution of individual pollutants to total

damages than there is about the contribution of individual pollutants to specific mechanisms, such uncertainty is invariably present in any decision that seeks to incorporate trade-offs among different environmental impacts. The endpoint methods used here have been designed to incorporate the available scientific knowledge about environmental mechanisms. This approach is potentially superior for decision-making than decisions based on a mid-point method, where the decision maker may at best apply qualitative consideration of that science.

Materials and methods

LCA model

This work builds on an integrated hybrid LCA model, THEMIS (technology hybridized environmental-economic model with integrated scenarios), which has been developed to evaluate life cycle impacts of global electricity system scenarios. THEMIS represents the global economy in nine regions, incorporating regional adaptations of the ecoinvent LCA database for materials and selected manufacturing processes and the EXIOBASE multiregional input-output model for inputs of services. The 2 °C and baseline scenarios of the Energy Technology Perspectives of the International Energy Agency provided parameters describing region-specific technology performance and electricity generation mixes in 2010, 2030 and 2050. Prospective LCAs of material production from the New Energy Externalities Development for Sustainability (NEEDS) project were used to represent important technology improvements in the mitigation scenario. The electricity generation is modeled in the foreground based on original inventories collected by a team of experts under the auspices of the International Resource Panel [17, 18]. A key feature of an increasingly clean power system is that more of the environmental impacts occur in the construction of the power system, and if needed, the provision of the fuels. Changes in the power system reduce the pollution caused in particular in manufacturing processes, creating a virtuous circle. We capture the positive feedback of clean electricity on the construction of the power system through integrating the foreground life cycle inventories of electricity production into the background by replacing electricity in ecoinvent and EXIOBASE. Thus, the model captures important improvements both in material production and in the electricity used in manufacturing. The THEMIS model is documented in a separate method paper [16] and has been applied in a number of assessments [19–26].

Life cycle inventories

Life cycle inventories for solar technologies (specifically photovoltaics and concentrating solar power), hydropower, wind power, natural gas, and coal power, were collected by a team of experts under the auspices of the International Resource Panel. These detailed bottom-up life cycle inventories of electricity generation technologies tally up emissions and resource use caused by the manufacturing of power plants and associated infrastructure, the production of fuels, and the operation and dismantling of power plants. The 450 page report of the Resource Panel offers a description of the technologies, the inventories, and further assessments, e.g. of the scientific literature on ecological impacts. We supplemented the original technology portfolio with data on nuclear power [26] and biopower based on forest residues and short-rotation coppice [27, 28]. Nuclear power inventories were adapted from ecoinvent 2.2 [29]. Biomass feedstocks can be classified in four main economic categories, from lower to higher costs: wastes (e.g. organic waste, manure), processing residues (e.g. timber residues, black liquor), locally collected feedstocks (e.g. agricultural and forestry residues, energy crops), and internationally traded feedstocks (e.g. roundwood or biomethane). These feedstocks may undergo pretreatment to improve transportation and conversion processes, such as drying, pelletisation, briquetting, torrefaction, pyrolysis, or hydrothermal upgrading [30]. Due to limited life cycle data available on each of these options, we principally modeled two types of biomass feedstocks used for electricity generation: forest residues and lignocellulosic biomass from short rotation wood crops. Across all regions and years, we assumed a fifty-fifty split between these two biomass feedstocks. In energy scenario literature, dedicated lignocellulosic, woody or grass-type energy crops is generally expected to be the most important type of biomass feedstock in the future. Agriculture or forestry residues, are often important, but their use varies across models. First generation energy crops, including sugar cane and palm oil crops, play only a small role in long-term scenarios [31, 32]. We assumed that short rotation wood crops is overall representative for lignocellulosic energy crops in general, a simplifying assumption that is also made in some energy scenario models (table S1 available at stacks.iop.org/ERL/12/034023/mmedia in electronic supplement of Rose *et al* [31]). For forest residue biomass, life cycle inventories were adapted from Singh *et al* [27]. For crop-based biomass, we used data on the amount of diesel, nitrogen, phosphorus and potassium fertilizer, chemicals and irrigation for existing bioenergy crops [28]. We also included inputs of diesel, fertilizer and chemicals to the production of cuttings [33]. For emissions of nitrogen compounds from crops, we assumed the following factors: 0.016 kg N_2O to air [34], 0.05 kg ammonia (NH_3) to air [35], 0.003 kg NOx to air [35], and 0.3 kg nitrate (NO_3^-) to water (derived from [34, 36]) per kg of N fertilizer added. Assumed emission factors for phosphorus compounds were: 0.5 kg phosphate and 0.2 kg particulate phosphorus to water per hectare per year, based on values reported in [35, 36]. We treated the use of herbicides and pesticides as emissions to agricultural soil. Fuel and auxiliary input requirements and emissions associated with the operation of biomass power plants to produce electricity was modelled based on ref [27]. For biopower, average global yields for the modelled energy crops were taken to be 190 GJ ha^{-1} yr^{-1} in 2010, 400 GJ ha^{-1} yr^{-1} in 2030, and 500 GJ ha^{-1} yr^{-1} in 2050, based on the most optimistic assumptions found in the literature (see figure 3 in [37]). Sensitivity analysis on feedstock mix is provided in the supplementary information (figure S3).

Impact assessment

The call for indicators aggregating different environmental mechanisms reflects the limits of considering many factors in decision making [38, 39]. Further, environmental impacts are only one aspect of technologies, along with cost, ease of operation, reliability, etc. Yet, scientists have been slow to embrace a comprehensive indicator, citing imperfection in knowledge that requires value judgments to resolve, and the incommensurability of risks or damages that affect different individuals, groups, species or ecosystems [40]. Typically, economists monetize ecosystem damages through estimates of external costs caused by pollution. In contrast, environmental scientists model the strengths of different environmental impacts and quantify their contribution to a common indicator, such as human health and ecosystem quality [41, 42]. While both approaches have been used in life cycle assessment (LCA), we prefer the latter approach, which is more accepted in LCA and subject to major research efforts. In this paper we applied ReCiPe [14], a widely used method for life cycle impact assessment, with many person-years of dedicated development effort. Many energy LCAs [16] rely on ReCiPe midpoint indicators, which express the contribution of product systems to a large set of environmental mechanisms (also called impact categories). Human health impacts of energy LCAs were previously analyzed by ref [43]. This letter reports the first assessment of potential damage to both human health *and* ecosystem quality caused at the endpoint level of all major electricity generation technologies, as well as global power system scenarios.

The ReCiPe indicator for damage to human health incorporates the aggregate effects of the following environmental mechanisms: air pollution, human toxicity (via carcinogenic and non-carcinogenic damage), ionizing radiation (carcinogenic and hereditary effects), and climate change (table 1). The term ‘air pollution’ represents the effects of particulate matter formation (inhalation exposure to particulate matter in the air), photochemical oxidant formation (inhalation exposure to ozone and other oxidants), and ozone depletion (exposure to increased UV radiation). Human health damage was measured in disability-adjusted life years (DALYs), which combine years lost due to premature mortality, and years lived with a disability, or in poor health [14]. The ecosystem quality indicator was calculated from aggregated species diversity effects of the following environmental mechanisms: terrestrial, freshwater and marine ecotoxicity (increased concentration of toxic chemicals), terrestrial acidification (change in base saturation), freshwater eutrophication (algae growth, hypoxia of aquatic milieus), and climate change (temperature increase and loss of species). The unit for damage to ecosystem quality is species.yr, derived from the potentially disappearing fraction (PDF) approach [44]. PDF is a measure quantifying the fraction of today’s present species that will potentially become extinct in a specific geographical location due to an emission or anthropogenic intervention. In that, it is a measure for loss of species richness, i.e. potential species extinction. PDF includes losses that happen right after the intervention, and also time-integrated damages. For example, a pulse of CO_2 emissions, still leads to species loss after 100 years. In ReCiPe [14], PDF was developed to species.yr, to have damages in absolute terms. The indicator species.yr is based on the species richness of different environmental compartments (freshwater, marine, terrestrial), which allows the damages in these compartments to be combined. ReCiPe is based on global species densities for these different environmental compartments, which are multiplied by the damage in PDF gives a weighted damage over all species in all compartments (assuming equal weight for all species). For the sake of legibility in presenting the final unit results, midpoint indicators with an endpoint characterization factor were aggregated into six distinct groups, as shown in table 1.

Scenario methods

Scenario assessment results were based on vintage capital modelling, as in [16, 45]. The electricity system life cycle inventories were broken down by life cycle stages: construction, operation and maintenance, and decommissioning. For every year from 2010 to 2050, the total environmental impact from the electricity sector was calculated as the sum of the environmental impacts of capacity increase (construction), the operation of existing plants, and the repowering of retired plants. The capacity figures were derived from the IEA’s Baseline and BLUE Map scenarios’ data on power plant installed capacities (table 2) [13]. Combining these capacity values with the lifetime of the various technologies, we were able to derive the capacity increase, operation, decommissioning and repowering rates for each technology and region. Finally, the indicators were all scaled to 100 in 2008 to show their relative variation until 2050.

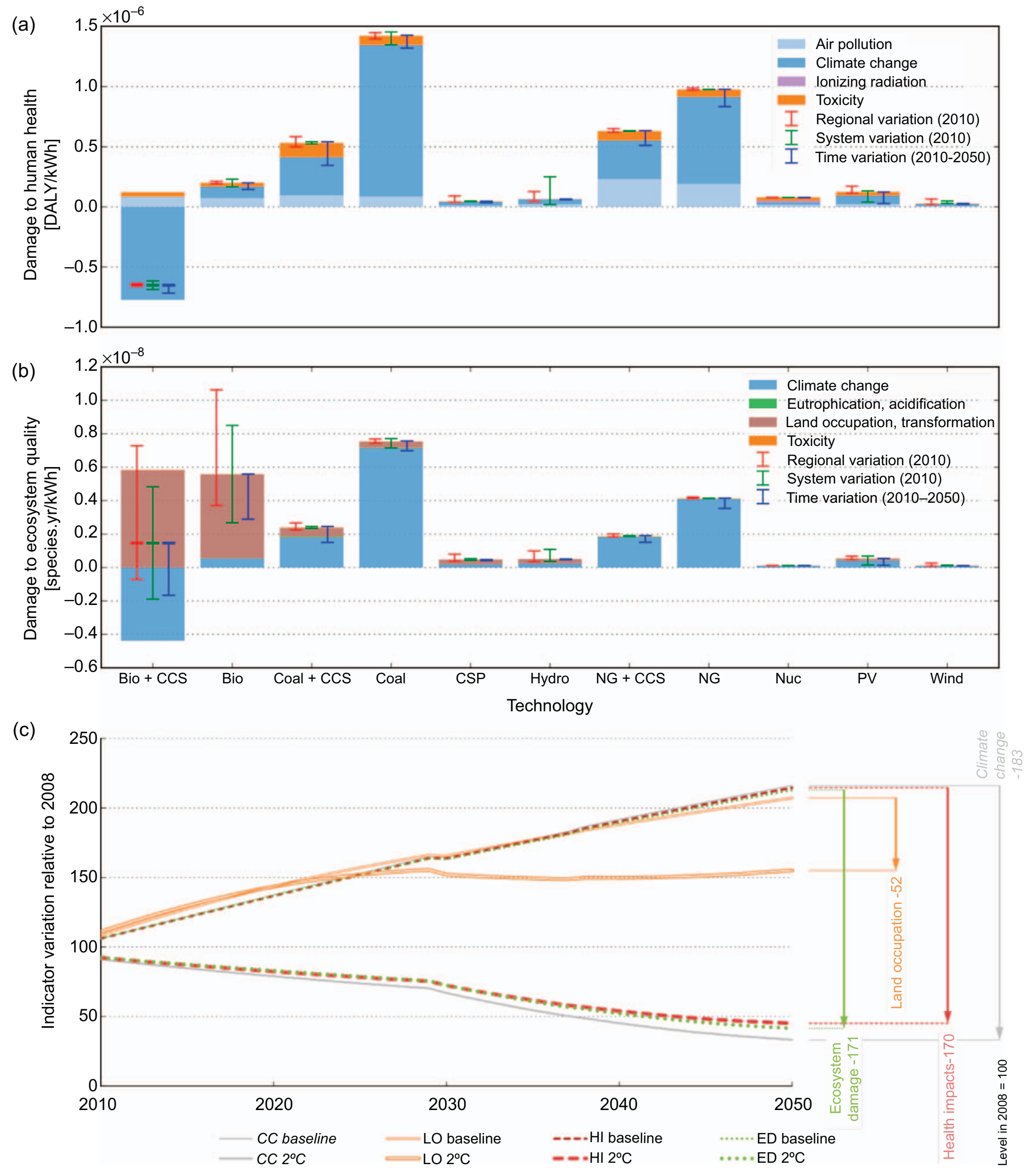

Figure 1. Unit results for the damage to human health (*a*) and ecosystem quality (*b*) of one kilowatt-hour of global mix electricity at grid. Environmental impacts from 2010 to 2050 following 2 °C and baseline scenarios (*c*), displaying human health, ecosystem quality, as well as indicators for greenhouse gas emissions, land occupation, which are the two most important environmental mechanisms. Panels (*a*) and (*b*) represent the impacts of global average electricity by technology in 2010. The figure summarizes results calculated for 9 regions, 12 technology clusters representing 37 systems, and the years 2010, 2030 and 2050 [15]. Regional, system, and time variations are represented by error bars, indicating the extremes of results for each technology. Regional variation is the range of results among regions for a given technology cluster, system variation is the range of results for systems within that technology cluster, and time variation is the variation in global average impacts of that technology cluster over the 2010–2050 timeline. All global results are based on a weighted average of regional production by more specific technological system. DALY stands for disability-adjusted life-years. Bio: Biopower, CCS: CO_2 capture and storage, CSP: concentrating solar power, NG: natural gas combined cycle power, Nuc: nuclear fission, PV: photovoltaics, CC: climate change (measured by CO_2 equivalents), LO: land occupation, HI: human health impact, ED: ecosystem damage.

Results

The results of our technology comparison indicate that renewable energy sources and nuclear power have lower human health impacts than coal or gas power (figure 1(*a*)). This advantage is mostly due to the lower impacts from climate change, which tend to dominate health impacts for all technologies including renewable energy. However, even without considering climate change, renewable and nuclear power perform better than fossil power. Solar, wind and hydropower have lower emissions for all classes of pollution than coal and gas power (see supporting material). We found lower human health impacts for coal and gas with CCS than without, given the reduced impacts from climate change. The impacts from all other environmental mechanisms were increased with CCS due to the additional energy and infrastructure required for the capture process. CCS thus offers CO_2 emission control but no co-benefits over fossil power with advanced pollution control equipment. Biopower is able to offset the climate impacts of fossil technologies when CCS is employed to ensure negative emissions. These avoided climate impacts are *larger* than the impacts of combustion-related air pollution and fuel-chain greenhouse gases, resulting in a net health benefit of biopower with CCS. Without CCS, the human health impacts of biopower are lower than those of fossil fuels but higher than those of other renewables and nuclear power. Solar or wind power plants, experience a significant variation of per-kWh impact across regions reflecting the quality of the resource (see figure S1 for a closer view of renewable technologies), whereas the widest variation for fossil-powered plants is over time, as more efficient technologies become mainstream and regulations more stringent. When employed on a large scale according to the 2 °C scenario, low-carbon technologies cut human health impacts from power generation in half by 2050. Without additional climate policy measures, increased electricity use and the large increase in coal power in the baseline scenario would more than double human health impacts (figure 1(*c*)).

Comparing the technologies in terms of impacts on ecosystem quality per kWh, we found the impact of land occupation for biopower to be of similar magnitude to the impact of GHG emissions from coal power. Even taking into account the ability of bioenergy with CCS to remove CO_2 from the atmosphere, bioenergy's ecological impact was as high as that of fossil power with CCS. For solar, wind, hydro and nuclear power, in contrast, we found very low impacts from all environmental mechanisms assessed here. CCS reduced ecosystem quality impacts from climate change, more than offsetting the increases in all other environmental mechanisms (figure 1(*b*)).

Our work relied on the implementation of power systems in average locations in each of the nine world regions, but ecosystem impacts of land occupation vary substantially depending on the ecological richness of the site. The choice of land on which biomass will be grown will affect ecosystem impacts substantially. Climate mitigation scenarios assume large increases in biomass yields, from 190 to 500 GJ ha^{-1} a^{-1} between 2010 and 2050 in the case of the IEA [46], which can also reduce ecosystem impacts of land occupation. Integrated land use modelling indicates that such yield increases might result from a dedicated policy of protecting natural landscapes, whether it is for preserving carbon storage on land through land carbon pricing [47] or for protecting ecosystems [48]. However, without such policies, economics favors expanded over intensive land use, which our results indicate would have an adverse ecological impact.

Assuming short of 4% of electricity from biomass and substantial increases in yield, ecosystem quality impacts in the 2 °C scenario would decrease by more than a half by 2050 given the significantly reduced impacts from climate change. By contrast, ecosystem quality impacts would more than double in the baseline scenario, due to climate change. With the exception of biopower, the diversified technology portfolio of the 2 °C scenario, in which nuclear, hydro, solar and wind power each produce more than one sixth of the global electricity [46], clearly offers ecological co-benefits over the coal-dominated baseline scenario. Non-climate ecological impacts grow in the 2 °C scenario, but slower than in the baseline scenario (figure S2).

To investigate the role of the yield, we conducted a break-even analysis of its influence on the damage to ecosystem quality of various biopower systems compared to fossil fuels (figure 2). The impact on ecosystem quality is inversely proportional to energy yield. The ecosystem impact of biopower, as used in the global mix in our assumptions (in blue on figure 2), breaks even with the impact of coal power at 127 GJ ha^{-1} yr^{-1} and of natural gas power at 293 GJ ha^{-1} yr^{-1}. The ecosystem impact of biopower with CCS breaks even with coal power with CCS at 156 GJ ha^{-1} yr^{-1} and with gas power CCS. Assumptions of global average energy yield from the literature on energy scenarios [37] are indicated in figure 2 for reference. These yields were anywhere between 162 GJ ha^{-1} yr^{-1} (without irrigation, IMAGE *[Integrated Model to Assess the Global Environment]* [49]) and 491 GJ ha^{-1} yr^{-1} (with irrigation, ReMIND *[Regionalized Model of Investments and Development]*/MAgPIE *[Model of Agricultural Production and its Impact on the Environment]* [50, 51]) in 2030. The human health and ecosystem impacts of irrigation systems did not contribute substantially to any of the mechanisms investigated here, but the achieved yield increases may be important to prevent biodiversity damage from biopower. If residues were not available and only short-rotation crops were used (in green on figure 2), the break-even yields with coal power were quite high and only achieved in the explicitly optimistic ReMIND/MAgPIE scenario.

Discussion

Assessing ecosystem impacts from bioenergy

The high ecosystem impact of biopower, with land use largely offsetting the benefits of CO_2 emission mitigation, is a novel finding. We hence would like to discuss bioenergy in more detail.

We do not account for potential land use change related emissions or the difference in timing between the emission of CO_2 and its uptake [52]. Life cycle GHG emissions of our biopower systems come mostly from fuel production and harvesting. Disregarding the impact of climate change, we find that the combustion-related emissions from fossil power and biopower

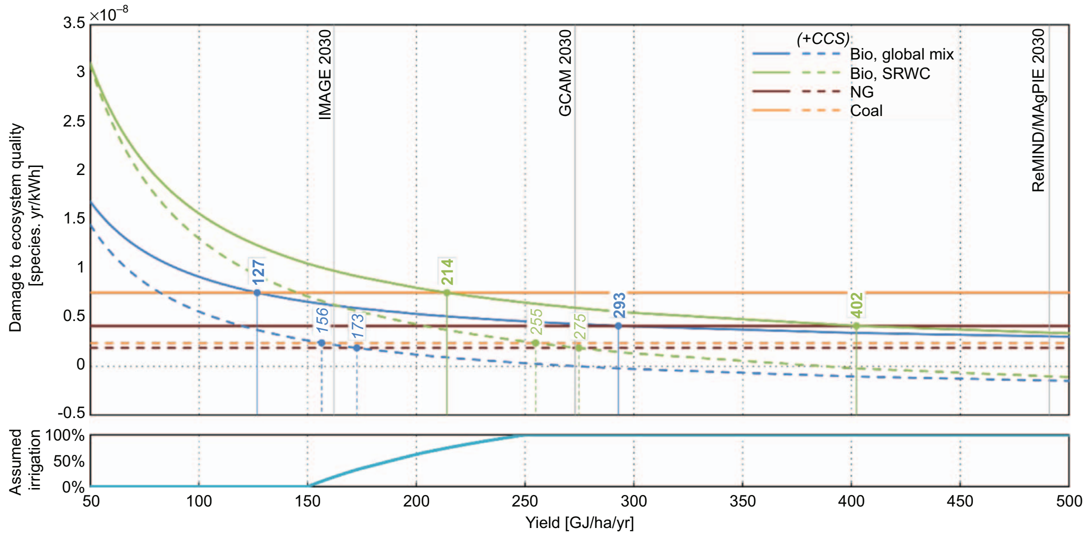

Figure 2. Influence of the energy yield, in GJ ha^{-1} yr^{-1}, on the ecosystem damage score of biopower technologies, in species.yr/kWh. Break-even values are shown for yields that bring the impact of biopower equal to that of coal or gas, with and without CCS. The 2030 value of three different models are shown in gray for comparison. 'Bio, global mix': biopower with global feedstock mix, 'Bio, SRWC': biopower with 100% short-rotation wood crops as feedstock. No irrigation is considered for yields under 150 GJ ha^{-1} yr^{-1}, 100% irrigation for yields over 250 GJ ha^{-1} yr^{-1}, irrigation rate is linearly interpolated relatively to land use between these values. Interpretation: biopower causes less damage to ecosystem quality than coal power if the assumed feedstock energy yield is higher than 214 GJ ha^{-1} yr^{-1}, or 255 GJ ha^{-1} yr^{-1} if both plants are built with CO_2 capture equipment.

cause larger human health impacts than technologies that do not rely on combustion for primary power generation.

Biopower shows a relatively high contribution to the ecosystem damage indicator from terrestrial ecotoxicity. The metolachlor used as herbicide during the agricultural phase is responsible for most of this contribution (more than 90%), due to a substantially larger ecotoxicity characterization factor. If this herbicide use is avoided, as it is for most of the biomass sources involved in the survey underlying our data [28], the ecotoxicity levels of biopower would fall below those of its fossil counterparts. Although classified as a potential carcinogen by the U.S. Environmental Protection Agency [53], metolachlor is widespread in the United States. The actual toxicity of metolachlor on humans and ecosystems is still being analyzed [53–56], and actual effects are difficult to assess because acute toxicity mostly occurs in combination with other substances [57].

Regarding land occupation, biomass plantations require about two orders of magnitude more surface area than any other technology, although the impact of this land use is less per unit area than that of coal mines. The high pressure of agricultural systems on ecosystems through land occupation is reflected in the endpoint indicators: the potential damage to ecosystems from biopower is comparable to the impact of coal power through climate change. One should note that land transformation (land use change) and land occupation (land use) are different impacts, with different consequences. Occupation impacts are impacts caused by ongoing land use, thus maintaining a changed ecosystem quality in comparison to a reference state, which effectively accounts for the delay in potential recovery. Transformation impacts relate to the one-time event of land use change, which in ReCiPe is modeled as the change in species richness during a recovery period [58].

We found that the choice of biomass feedstock supply considerably alters land occupation impacts of bio-sourced electricity generation. Depending on the feedstock, and its assumed energy yield, these impacts may be as large as 0.46 m^2a kWh^{-1} for crop-based biomass with CCS if implemented today, to as little as 0.06 for forest residues and 2050 efficiencies. At a global level, the feedstock mix influences significantly the stress on land occupation (figure S3). For forest residues as feedstock, we did not account for the land occupation associated with the forest area from which the residues are sourced because timber is the main output of forestry, and the choice to harvest forest residues (in addition to timber) does not increase the forest area needed. Implementing methods for assessing the ecological impact of removing this extra biomass from the forest would require more information on the operations on the ground [59], but could potentially nuance our results. Adopting an endpoint perspective on the deployment of low-carbon electricity generation—that is, focusing on the ultimate damage to ecosystems and human health—shows that land occupation may become a major contributor to the threat to ecosystems. This finding is not surprising, because land use is already one of the main drivers of global biodiversity loss [60].

In general, methods for quantifying impacts on ecosystem quality in LCA are fast developing, including the introduction of additional stressors, finer spatial detail and inclusion of taxa-specific characteristics or vulnerabilities. As is also the case for this study, land use very often turns out to be a dominant driver of impacts on biodiversity and therefore deserves special attention. In the last decade numerous methods for quantifying impacts from land use have been proposed in an LCA context, ranging from methods specific to individual countries or taxonomic groups to methods that are applicable on a global level and for multiple land use types, spatial levels and taxonomic groups. Curran *et al* [61] provide an overview of 20 land use models developed for LCA assessments. The dominant metric for current land use methods is 'species richness' (16 of the models in Curran *et al*), which restricts the assessments to changing species numbers, but does not include other information, such as abundance or vulnerability. Most of the currently used and proposed land use methods are related to endpoint indicators, very frequently the potentially disappeared fraction of species (PDF). However, discussions whether absolute species losses (instead of relative ones) would not be more meaningful are ongoing [58], especially because losses at local and global levels can be wrongly assumed to be the same [42]. Currently, midpoint indicators used for land use assessments are usually restricted to the quantification of the amounts of land used or transformed, which the inventory parameters [58]. While this is easy to quantify, it does not reflect impacts very well.

The UNEP-SETAC life cycle initiative has recently made a first recommendation for a land use assessment method, which is quantifying impacts for 6 different taxonomic groups for 6 different land use types in all 825 terrestrial ecoregions of the world and includes the vulnerability of species. However, the method is also only developed on an endpoint level and, due to its novelty and therefore limited experience in test cases, recommended for hotspot analyses only [62].

Also, while spatial aspects have gained attention in recent years, this is much less the case for temporal aspects, such as dependencies on the timing of harvesting of agricultural crops [58].

The methods we employed to quantify environmental impacts are state-of-the-art, however, the characterization factors used to convert life cycle inventory values to environmental impact scores would be more accurate if they were spatially explicit. The characterization factors represent an average of all global ecosystems and habitats, but the impacts depend on local circumstances. In emerging spatially-explicit impact assessment methods, such as LC-Impact [63], spatial differentiation includes ecoregion, watershed or even pixel level detail, and leads to widely varying characterization factors due to differences in ecosystem sensitivity or species richness [59]. For example, the ecosystem impacts of land use can vary by up to four orders of magnitude among the various ecoregions and land use types [64]. This wide range leads to a larger variation in results. However, the poorest ecoregions are not very productive, so the actual impact for realistic biomass supply scenarios will not vary as much. These emerging spatially explicit assessment methods could not be applied to the present inventory results because the energy scenarios that are available do not specify the location where biomass is harvested. Employing spatially explicit impact assessment would require systematic spatial detail in energy scenarios and life cycle inventory data. Given the importance of land use for the ecosystem impacts of future energy systems, it would be pertinent to develop such scenarios and inventory data in order to explore the potential of growing biomass in areas of lower ecosystem diversity, which again can be used to derive policies that ensure that feedstock will in fact be sourced from such low-impact regions. Such scenarios would consider a wider variety of biomass sources and conversion technologies.

Robust co-benefits

Our LCA results are robust with respect to the substantial co-benefits of replacing coal and gas with solar, wind, hydro and nuclear power for both human health and ecosystem quality. These co-benefits are a result of the significant air and water pollution caused by extraction, transport and combustion of coal and gas, as well as the substantial land use associated with coal mining. These patterns were already suggested by analyses of individual environmental mechanisms [16] or individual pollutants [8–10] rather than integrated endpoints. High non-CO_2 pollution impacts for CCS have been consistently found in the LCA literature [65–67], although other works suggests that impacts may be comparable [11]. Our work confirms these findings but also indicates that the avoided climate change impacts are larger than the additional non-climate pollution impacts.

There are significant trade-offs for ecosystem quality associated with biopower and smaller trade-offs associated with pollution from fossil power with CCS. From a co-benefit perspective, the reliance on a large-scale utilization of biopower, not least to achieve negative emissions after 2050, appears to be a weak point of present mitigation scenarios [68]. To understand the potential ecosystem damage of increased land occupation and changed emissions better, future research should develop scenarios for the location of biomass plantations and power plants, allowing the application of methods for site-specific impact assessment [64]. A larger variety of biomass supplies may be explored, with value-chain specific ecological impacts. Our present analysis considers a combination of forest residues and fast rotation croppies, which have relatively small land use impacts compared to conventional forestry or agriculture. To limit ecosystem quality impacts, policy makers should seek technology and management options for ensuring a biomass supply with lower than average land use impacts. Our findings also provide a rationale for investigating alternative carbon-negative technologies that lead to lower land use impacts.

The findings of our work should put to rest residual myths about adverse health and ecosystem impacts associated with the high energy use and material requirements of producing and installing solar and wind power plants and put in perspective the health impacts associated with ionizing radiation from nuclear power. Adopting the right mix of low-carbon technologies for electricity generation brings multiple benefits to human and ecosystem health while having the potential to stabilize global temperature.

Author contributions

EH conceived of the research, TG constructed the model, TG, AA, and EH carried out the analysis, AA and BS contributed the data on biopower, EH, TG, AA, FV wrote up the manuscript.

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References

[1] Dubash N K, Hagemann M, Höhne N and Upadhyaya P 2013 Developments in national climate change mitigation legislation and strategy *Clim. Policy* **13** 649–64

[2] Somanathan E *et al* 2014 National and sub-national policies and institutions *Climate Change 2014: Mitigation of Climate Change* ed O Edenhofer *et al* (Geneva: Intergovernmental Panel on Climate Change)

[3] Bruckner T *et al* Energy systems *Climate Change 2014: Mitigation of Climate Change* ed O Edenhofer *et al* (Geneva: Intergovernmental Panel on Climate Change) 2014

[4] Ürge-Vorsatz D, Herrero S T, Dubash N K and Lecocq F 2014 Measuring the co-benefits of climate change mitigation *Annu. Rev. Environ. Resour.* **39** 549–82

[5] von Stechow C *et al* 2015 Integrating global climate change mitigation goals with other sustainability objectives: a synthesis *Annu. Rev. Environ. Resour.* **40** 363–94

[6] Hellweg S and Milà i Canals L 2014 Emerging approaches challenges and opportunities in life cycle assessment *Science* **344** 1109–13

[7] Blanco G *et al* 2014 Drivers trends and mitigation *Climate Change 2014: Mitigation of Climate Change* ed O Edenhofer *et al* (Cambridge: Cambridge University Press)

[8] Turconi R, Boldrin A and Astrup T 2013 Life cycle assessment (LCA) of electricity generation technologies: overview comparability and limitations *Renew. Sust. Energ. Rev.* **28** 555–65

[9] Masanet E, Chang Y, Gopal A R, Larsen P, Morrow W R, Sathre R, Shehabi A and Zhai P 2013 Life-cycle assessment of electric power systems *Annu. Rev. Environ. Res.* **38** 107–36

[10] Treyer K and Bauer C 2016 Life cycle inventories of electricity generation and power supply in version 3 of the ecoinvent database—part I: electricity generation *Int. J. Life Cycle Assess.* **21** 1236–54

[11] Volkart K, Bauer C, Burgherr P, Hirschberg S, Schenler W and Spada M 2016 Interdisciplinary assessment of renewable nuclear and fossil power generation with and without carbon capture and storage in view of the new Swiss energy policy *Int. J. Greenhouse Gas Control* **54** 1–14

[12] Treyer K and Bauer C 2016 The environmental footprint of UAE's electricity sector: combining life cycle assessment and scenario modeling *Renew. Sust. Energ. Rev.* **55** 1234–47

[13] IEA 2010 *Energy Technology Perspectives 2010: Scenarios and Strategies to 2050* (Paris: OECD/IEA) p 650

[14] Goedkoop M, Heijungs R, Huijbregts M, Schryver A D, Struijs J and Zelm R V 2013 *ReCiPe 2008: A Life Cycle Impact Assessment Method which Comprises Harmonised Category Indicators at the Midpoint and the Endpoint Level* revised edition (Den Haag: Ministry of Housing, Spatial Planning and Environment)

[15] Gibon T, Wood R, Arvesen A, Bergesen J D, Suh S and Hertwich E G 2015 A methodology for integrated, multiregional life cycle assessment scenarios under large-scale technological change *Environ. Sci. Technol.* **49** 11218–26

[16] Hertwich E G, Gibon T, Bouman E A, Arvesen A, Suh S, Heath G A, Bergesen J D, Ramirez A, Vega M I and Shi L 2015 Integrated life-cycle assessment of electricity-supply scenarios confirms global environmental benefit of low-carbon technologies *Proc. Natl Acad. Sci. USA* **120** 6277–82

[17] Hertwich E G *et al* 2016 *Green Energy Choices: The Benefits, Risks and Trade-offs of Low-Carbon Technologies for Electricity Production* (Nairobi, Kenya and Paris, France: United Nations Environment Programme)

[18] Bergesen J D, Tähkämö L, Gibon T and Suh S 2016 Potential long-term global environmental implications of efficient light-source technologies *J. Ind. Ecol.* **20** 263–75

[19] Beucker S, Bergesen J D and Gibon T 2016 Building energy management systems: global potentials and environmental implications of deployment *J. Ind. Ecol.* **20** 223–33

[20] Kulczycka J, Lelek Ł, Lewandowska A, Wirth H and Bergesen J D 2016 Environmental impacts of energy-efficient pyrometallurgical copper smelting technologies: the consequences of technological changes from 2010 to 2050 *J. Ind. Ecol.* **20** 304–16

[21] Nahlik M J, Kaehr A T, Chester M V, Horvath A and Taptich M N 2016 Goods Movement life cycle assessment for greenhouse gas reduction goals *J. Ind. Ecol.* **20** 317–28

[22] Taptich M N, Horvath A and Chester M V 2016 Worldwide greenhouse gas reduction potentials in transportation by 2050 *J. Ind. Ecol.* **20** 329–40

[23] Berrill P, Arvesen A, Scholz Y, Gils H C and Hertwich E G 2016 Environmental impacts of high penetration renewable energy scenarios for Europe *Environ. Res. Lett.* **11** 014012

[24] Bergesen J D, Heath G A, Gibon T and Suh S 2014 Thin-film photovoltaic power generation offers decreasing greenhouse gas emissions and increasing environmental co-benefits in the long term *Environ. Sci. Technol.* **48** 9834–43

[25] Singh B, Bouman E A, Strømman A H and Hertwich E G 2015 Material use for electricity generation with carbon dioxide capture and storage: extending life cycle analysis indices for material accounting *Resour. Conserv. Recy.* **100** 49–57

[26] Dones R 2007 *Nuclear Energy—Ecoinvent Report No. 6-VII* (Villingen: Swiss Centre for Life Cycle Inventories)

[27] Singh B, Guest G, Bright R M and Strømman A H 2014 Life cycle assessment of electric and fuel cell vehicle transport based on forest biomass *J. Ind. Ecol.* **18** 176–86

[28] Njakou Djomo S, Ac A, Zenone T, De Groote T, Bergante S, Facciotto G, Sixto H, Ciria Ciria P, Weger J and Ceulemans R 2015 Energy performances of intensive and extensive short rotation cropping systems for woody biomass production in the EU *Renew. Sust. Energ. Rev.* **41** 845–54

[29] Frischknecht R and Jungbluth N 2007 *Ecoinvent 2* (Dübendorf: Swiss centre for Life Cycle Inventories)
[30] International Energy Agency 2012 *Technology Roadmap Bioenergy for Heat and Power* (Paris: IEA Publications)
[31] Rose S K, Kriegler E, Bibas R, Calvin K, Popp A, van Vuuren D P and Weyant J 2014 Bioenergy in energy transformation and climate management *Clim. Change* **123** 477–93
[32] van Vuuren D P, Bellevrat E, Kitous A and Isaac M 2010 Bio-energy use and low stabilization scenarios *Energy J.* **31** 193–221
[33] Njakou Djomo S *et al* 2013 Energy and climate benefits of bioelectricity from low-input short rotation woody crops on agricultural land over a two-year rotation *Appl. Energ.* **111** 862–70
[34] IPCC 2006 *2006 IPCC guidelines for national greenhouse gas inventories. Volume 4: Agriculture, forestry and other land use. Chapter 11: N_2O emissions from managed soils, and CO_2 emissions from lime and urea application*
[35] Faist Emmenegger M, Reinhard J and Zah R 2009 *Sustainability quick check for biofuels—intermediate background report*
[36] Nemecek T and Kägi T 2007 *Life Cycle Inventories of Agricultural Production Systems* (Dübendorf: Swiss Center for Life Cycle Inventories)
[37] Popp A *et al* 2013 Land-use transition for bioenergy and climate stabilization: model comparison of drivers, impacts and interactions with other land use based mitigation options *Clim. Change* **123** 495–509
[38] Kahneman D 2011 *Thinking Fast and Slow* (New York: Farrar, Straus and Giroux)
[39] Cartelle Barros J J, Lara Coira M, de la Cruz López M P and del Caño Gochi A 2015 Assessing the global sustainability of different electricity generation systems *Energy* **89** 473–89
[40] Hertwich E G, Hammitt J K and Pease W S A 2000 Theoretical foundation for life-cycle assessment: recognizing the role of values in environmental decision making *J. Ind. Ecol.* **4** 13–28
[41] Curran M, De Baan L, De Schryver A M, Van Zelm R, Hellweg S, Koellner T, Sonnemann G and Huijbregts M A J 2011 Toward meaningful end points of biodiversity in life cycle assessment *Environ. Sci. Technol.* **45** 70–9
[42] Hofstetter P 1998 *Perspectives in Life Cycle Impact Assessment: A Structured Approach to Combine Models of the Technosphere, Ecosphere and Valuesphere* (Boston, MA: Kluwer)
[43] Treyer K, Bauer C and Simons A 2014 Human health impacts in the life cycle of future European electricity generation *Energy Pol.* **74** (Supplement 1) S31–S44
[44] van de Meent D and Huijbregts M A J 2005 Calculating life-cycle assessment effect factors from potentially affected fraction-based ecotoxicological response functions *Environ. Toxicol. Chem.* **24** 1573–8
[45] Arvesen A and Hertwich E G 2011 Environmental implications of large-scale adoption of wind power: a scenario-based life cycle assessment *Environ. Res. Lett.* **6** 045102
[46] International Energy Agency 2015 *Energy Technology Perspectives 2015—Mobilising Innovation to Accelerate Climate Action* (Paris: IEA Publications)
[47] Humpenöder F *et al* 2015 Land-use and carbon cycle responses to moderate climate change: implications for land-based mitigation? *Environ. Sci. Technol.* **49** 6731–9
[48] Kraxner F *et al* 2013 Global bioenergy scenarios—Future forest development, land-use implications, and trade-offs *Biomass Bioenergy* **57** 86–96
[49] Bouwman A F, Kram T and Goldewijk K K 2006 *Integrated Modelling of Global Environmental Change. An Overview of IMAGE 2.4* (The Netherlands: Bilthoven)
[50] Popp A, Lotze-Campen H, Leimbach M, Knopf B, Beringer T, Bauer N and Bodirsky B 2011 On sustainability of bioenergy production: Integrating co-emissions from agricultural intensification *Biomass Bioenergy* **35** 4770–80
[51] Klein D *et al* 2014 The value of bioenergy in low stabilization scenarios: an assessment using REMIND-MAgPIE *Clim. Change* **123** 705–18
[52] Cherubini F, Peters G P, Berntsen T, Strømman A H and Hertwich E 2011 CO_2 emissions from biomass combustion for bioenergy: atmospheric decay and contribution to global warming *GCB Bioenergy* **3** 413–26
[53] Silver S R, Bertke S J, Hines C J, Alavanja M C R, Hoppin J A, Lubin J H, Rusiecki J A, Sandler D P and Beane Freeman L E 2015 Cancer incidence and metolachlor use in the agricultural health study: an update *Int. J. Cancer* **137** 2630–43
[54] Lin Y.-J, Karuppiah M, Shaw A and Gupta G 1999 Effect of simulated sunlight on atrazine and metolachlor toxicity of surface waters *Ecotoxicol. Environ. Safe.* **43** 35–7
[55] Ebenezer V and Ki J-S 2013 Quantification of toxic effects of the herbicide metolachlor on marine microalgae Ditylum brightwellii (Bacillariophyceae), Prorocentrum minimum (Dinophyceae), and Tetraselmis suecica (Chlorophyceae) *J. Microbio.* **51** 136–9
[56] Coquillé N, Jan G, Moreira A and Morin S 2015 Use of diatom motility features as endpoints of metolachlor toxicity *Aquat. Toxicol.* **158** 202–10
[57] Stepi S, Hackenberger B K, Velki M, Hackenberger D K and Lon ari Z 2013 Potentiation effect of metolachlor on toxicity of organochlorine and organophosphate insecticides in earthworm eisenia andrei *B. Environ. Contam. Tox.* **91** 55–61
[58] Milà i Canals L and de Baan L 2015 Land use *Life Cycle Impact Assessment* ed Z M Hauschild and A J M Huijbregts (Dordrecht: Springer) pp 197–222
[59] Huijbregts M A J *et al* 2014 *LC-IMPACT 2015—A spatially differentiated life cycle impact assessment approach (First batch released)*
[60] Mooney H A *et al* 2005 *Ecosystems and Human Well-Being: Synthesis* (Washington, DC: Island Press) p 137
[61] Curran M, Maia de Souza D, Antón A, Teixeira R F M, Michelsen O, Vidal-Legaz B, Sala S and Milà i Canals L 2016 How well does LCA model land use impacts on biodiversity?—A comparison with approaches from ecology and conservation *Environ. Sci. Technol.* **50** 2782–95
[62] Milà I Canals L, Antón A, Bauer C, de Camillis C, Freiermuth Knuchel R, Grant T, Michelsen O, Stevenson M Land Use related impacts on biodiversity *Global guidance for life cycle impact assessment indicators—Volume 1. Publication of the UNEP/SETAC Life Cycle Initiative* ed R Frischknecht and O Jolliet (Paris, France: United Nations Environment Programme)
[63] Verones F *et al* 2016 *LC-IMPACT Version* 0.5- A spatially differentiated life cycle impact assessment approach (www.lc-impact.eu/) (Accessed: 19 July 2016)
[64] Verones F, Huijbregts M A J, Chaudhary A, de Baan L, Koellner T and Hellweg S 2015 Harmonizing the assessment of biodiversity effects from land and water use within LCA *Environ. Sci. Technol.* **49** 3584–92
[65] Ramírez A R *et al* 2015 Chapter 3. Fossil fuels and carbon dioxide capture and storage *Environmental Assessment of Low-GHG Electricity Supply Technologies: IRP Report* ed E G Hertwich, T Gibon, S Suh, J Aloisi de Larderel and I R Panel (Nairobi, Kenya: United Nations Environment Programme) p 145
[66] Singh B, Strømman A H and Hertwich E G 2011 Comparative life cycle environmental assessment of CCS technologies *Int. J. Greenhouse Gas Control* **5** 911–21
[67] Corsten M, Ramírez A, Shen L, Koornneef J, Faaij A 2013 Environmental impact assessment of CCS chains—Lessons learned and limitations from LCA literature *Int. J. Greenhouse Gas Control* **13** 59–71
[68] Fuss S *et al* 2014 Betting on negative emissions *Nature Clim. Change* **4** 850–3