Life Cycle Assessment Demonstrates Environmental Co-Benefits and Trade-Offs of Low-Carbon Electricity Supply Options

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ABSTRACT: The targeted transition towards an electricity system with low or even negative greenhouse gas emissions affords a chance to address other environmental concerns as well, but may potentially have to adjust to the limited availability of assorted non-fossil resources. Life cycle assessment (LCA) is widely recognized as a method appropriate to assess and compare product systems taking into account a wide range of environmental impacts. Yet, LCA could not inform the latest assessment of co-benefits and trade-offs of climate change mitigation by the Intergovernmental Panel on Climate Change due to the lack of comparative assessments of different electricity generation technologies addressing a wide range of environmental impacts and using a consistent set of methods. This paper contributes to filling this gap. A consistent set of life cycle inventories of a wide range of electricity generation technologies is assessed using the Recipe midpoint methods. The life-cycle inventory modeling addresses the production and deployment of the technologies in nine different regions. The analysis shows that even though low-carbon power requires a larger amount of metals than conventional fossil power, renewable and nuclear power leads to a reduction of a wide range of environmental impacts, while CO_2 capture and storage leads to increased non-GHG impacts. Biomass has relatively modest co-benefits, if at all. The manufacturing of low-carbon technologies is important compared to their operation, indicating that it is important to choose the most desirable technologies from the outset.

KEYWORDS: hybrid life-cycle assessment, climate change mitigation scenario, wind power, photovoltaics, concentrating solar power, bioenergy with CCS (BECCS), nuclear energy, geothermal energy, coal power, natural gas combined cycle

1 Introduction

Electricity production is the most important contributor to anthropogenic climate change, with 25% of global greenhouse gas (GHG) emissions in 2010. Given the growth of gadgets and information technology as well as the replacement of hydrocarbon fuels as energy carriers, the role of electricity rises in practically all energy scenarios [1]. A stabilization of the global temperature can only be achieved when CO_2 emissions from electricity production are reduced radically and eventually go to zero. As of 2015, fossil power plants provide two thirds of global electricity [2]. Many electricity generation technologies can achieve lower GHG emissions per kWh than conventional coal, gas or oil fired power plants: solar, wind, hydro, nuclear, biomass, and geothermal power [3-6]. The capture of CO_2 from fossil power plants and its storage in geological reservoirs will also lower emissions to the atmosphere. The Intergovernmental Panel on Climate Change (IPCC) has investigated a wide range of scenarios consistent with the political target of limiting global warming to 2°C above pre-industrial level. Virtually all 2°C scenarios depend on a phasing out of unmitigated fossil fuel power plants shortly after 2050.[1] Fossil fuel extraction and use is also a major source of air, water and soil pollution [7], giving rise to hopes about co-benefits of climate change mitigation such as reduced health impacts and ecological damages. However, low-carbon power technologies also cause environmental impacts throughout their life cycle, including in their construction and decommissioning. These impacts differ from technology to technology. The potential transition towards a low-carbon energy system presents a major opportunity to reduce other environmental impacts as well, but we can realize this opportunity only if we understand the environmental impacts of different technologies and choose technologies accordingly.

The IPCC has relied on life cycle assessment (LCA) to compare different energy technologies in terms of the GHG emissions reductions offered per unit of conventional power replaced [3]. The IPCC has also reported life-cycle emissions of selected air pollutants of energy technologies [1, 8]; however, without attempting any assessment of the resulting environmental impacts. A major obstacle in the IPCC's assessment of the literature was that published studies of individual technologies use different assumptions and impact assessment methods, so that results among studies as published in the literature are not comparable for indicators other than CO_2-equivalent. Further, studies often fail to document inventory results, which would facilitate applying a common impact assessment method and thus allow a comparison of results [4-6]. Recent reviews have reported selected life cycle inventory results [4-6]. The data assembled for IPCC was based on a review of the literature, in which the Special Report on Renewable Energy [3] compared data as reported in the literature, while the AR5 [9, 10] relied on harmonized emissions [11-16] where such were available.

While a valuable first step, a review of inventory results is not sufficient to meet the need for a broader assessment of life-cycle environmental impacts of electricity generation. Policy development needs a more systematic effort to model environmental impacts of different electricity generation technologies in a comparative manner, using consistent assumptions, common life cycle inventories for similar inputs such as materials and transport, and the same impact assessment methods. A good example of such a study is the analysis of health effects associated with power generation under European conditions [17] conducted using the ecoinvent database. Climate research, including climate change modeling and integrated assessment modeling of climate change scenarios show the value of large-scale comprehensive studies, model comparison exercises, and similar integrative work. LCA has seen a lot of community effort in method development, primarily through the International Standards Organization and the Life Cycle Initiative of the United Nations Environment Programme (UNEP) and the Society of Environmental Toxicology and Chemistry (SETAC). There has been much less integrative focus on understanding what LCA can tell us about climate change mitigation. Analysts may have a general understanding of the technologies, but the IPCC must rely on peer-reviewed literature, which currently lacks in comparative and forward-looking analysis. The present paper reviews the first integrative assessment of the environmental co-benefits and adverse side effects of low-carbon electricity generation, which was conducted for the International Resource Panel (IRP) under the auspices of the United Nations Environment Programme (UNEP) [18]. The work of the IRP drew on a broad review of the literature on environmental impacts of electricity generation, including ecological studies of specific impacts and projects [19, 20], risk assessments [21], and studies of air pollution co-benefits of climate change mitigation [22]. However, such studies normally do not take into account life cycle issues, which are important especially for low-carbon energy options [23].

In this paper, we add bioenergy and nuclear power to the technologies analyzed for the International Resource Panel (IRP), that is, photovoltaics, concentrating solar power, on-shore and off-shore wind power, hydropower, geothermal power, different technologies for coal power including supercritical pulverized coal power and integrated gasification combined-cycle systems, with and without CO_2 capture and storage, and natural gas combined cycle systems. The present work extends our previous analysis of headline results [23] to a broader range of life-cycle impact categories, reports the results of the contribution analysis for each individual technology, and presents a comparison of the life cycle GHG emissions to those reported by the IPCC in the Special Report on Renewable Energy (SRREN) [3] and the 5th assessment report (AR5) [10].

2 Methods

2.1 Integrated Life Cycle Model

For the purpose of this assessment, a team of scientists including the present authors developed an integrated hybrid LCA model representing the global economy in nine world regions[24]. The model, THEMIS (technology hybridized environmental-economic model with integrated scenarios) was documented in detail in reference [24], where methodological choices were identified and justified. This hybrid LCA model combines foreground life cycle inventories assembled by expert teams under the auspices of the IRP with a background inventory database [25] and a global, nine-region input-output model [26, 27]. Inventories thus comprise both inputs of materials and energy carriers from the background database and purchase of services from the input-output model. THEMIS is integrated in the sense that the energy technologies described in this study are connected to the background and thus constitute the power stations providing electricity with which new power stations are manufactured, with an electricity mix based on scenario assumptions specified in section 2.3 [18].

2.2 Life cycle inventories

Several teams of scientists have provided life cycle inventory data for coal and gas power with and without CO_2 capture [28, 29], hydropower [30], wind power [31-33], photovoltaics [34, 35], and concentrating solar power [36, 37]. In addition to the life cycle inventories assembled for the IRP study, we developed inventories covering mainstream biopower technologies and added nuclear power.

For biopower, two systems were analyzed, one representing lignocellulosic biomass production from fast rotation energy crops, the second representing forest residue. The operation of biomass power plants to produce electricity is modelled based on data from [38]. For bioenergy crops, we utilize inventories of diesel, fertilizer, chemical and irrigation inputs to crop production, as well as land use and direct field emissions of CO_2, pesticides, nitrogen and phosphorus compounds, established by [39]. Here, the basic procedure is as follows: First, establish initial inventories based on survey data for existing bioenergy plantations [40], and other data sources; and then, adapt the inventories to the multi-regional and prospective THEMIS framework. In the inventory data used in present study, biomass yield per unit area and year vary across regions and years under the assumption that irrigation is allowed and with no restriction on the type of lignocellulosic biomass which may be used. In addition to lignocellulosic biomass from crops, we model forest residue biomass, utilizing inventories from [38]. Across all regions and years, we assume biomass is supplied by a fifty-fifty split between woody crops and forest residue. The present assessment does not include results for indirect land use. Integrated assessment modeling exercises indicate that the amount of land use change required per unit biopower depends on policies and is thus highly scenario-specific [43]; it does not so much reflect technology characteristics, which are the focus of the present work.

We have also added two nuclear power plant types from ecoinvent 2.2 [44]. We were not successful in resolving the issue regarding the large divergence between process-based results and input-output-based results identified by previous analyses [15, 45]. As a process-based LCA database, ecoinvent does not reflect activities such as planning and security that nuclear power requires to a much larger degree than other power plant types, resulting in a cut-off error that is likely to be larger than for other technologies. However, it was important for us to capture those environmental impacts that are specific to nuclear power, which we do through modeling the foreground system.

2.3 Scenario adaptations

The electricity mixes of each of the nine world regions come from the scenarios of the International Energy Agency's Energy Technology Perspectives (ETP) report [46], which reports such data for the years 2010, 2030 and 2050. The operating conditions of power plants, such as load factors, efficiencies and resource characteristics, e.g. insolation and wind strength, also vary by region reflecting the scenario assumptions of the ETP. For the present study, we conducted attributional life cycle inventory calculations that implicitly assume that a power plant is constructed, operated and dismantled using technology (background economy) of those specific years representing a specific world region for which the investigated technology is especially relevant.

2.4 Impact assessment

The life cycle impact assessment was based on the ReCiPe 1.08 method [47] from which the following list of indicators is selected: climate change, freshwater ecotoxicity, freshwater eutrophication, human toxicity, metal depletion, particulate matter emissions, photochemical ozone formation, terrestrial acidification, and land occupation (urban and arable)[47]. Categories available but left out are: marine eutrophication and ecotoxicity, excluded because of the high uncertainty in the characterization factor development; terrestrial ecotoxicity, excluded because of the results' redundancy with freshwater ecotoxicity; natural land transformation and water depletion, were excluded because relevant stressors were not accounted in some of the foreground systems; and fossil resource depletion was excluded because of a high correlation with climate change. This smaller number of indicators also better reflects their relative importance in the assessment of endpoint indicators, which is broadly in line with the importance of those themes in the comparative burden of disease [48] and the Millennium Ecosystem Assessment [49], see also [7].

3 Results

An overview of LCA results for all investigated technologies and indicators is provided in Figure 1, with results reported for both 2010 and prospective 2050 systems. Over their life-cycle, renewable energy technologies require substantial amounts of materials, leading to a high metal depletion indicator. The fossil energy sources, on the other hand, require large amounts of fossil fuels, leading to a higher overall resource depletion indicator (not shown here). In spite of their high material demand, renewable energy technologies have significantly lower pollution-related environmental impacts. The use of CCS reduces life-cycle greenhouse gas emissions of fossil technologies, but increases resource use and most other environmental impacts. These results hold broadly, but are sensitive to local conditions and features of specific projects. In the following, we address the results for each technology category and indicate some of the sensitivities.

3.1 Coal power

Fossil fuels are the dominant source of electricity today. Given the long lifetime of mines, wells, transport facilities, and power stations and the versatile nature of the fuel itself, fossil fuels are expected to remain an important source of electricity in the foreseeable future in many climate mitigation scenarios [50]. In most of these scenarios, CO_2 capture and storage plays an important role, allowing for a faster and less expensive reduction of CO_2 emissions, given assumptions about cost developments [51, 52]. The introduction of supercritical and ultrasupercritical coal power plants is a significant recent development that has raised the efficiency from 35-37% for subcritical to 43-45% for ultrasupercritical plants. Integrated gasification combined cycle plants serve as a new technological approach that achieves similar efficiencies, with the promise of further increases

[53-55]. The results show a trade-off between GHG mitigation and other environmental impacts. Subcritical coal power plants generally have higher impacts than supercritical and integrated gasification plants and much higher emissions than natural gas combined cycle plants (

Figure 1). With CCS, the GHG emissions of these modern power plants can be reduced by about three quarters, to 22-26% of existing coal power plants. Comparing modern plants with and without CCS indicates that CCS increases almost all impact categories by 20-60% compared to the non-CCS alternatives. We have also analyzed the contribution of different life cycle steps (Figure S1). For a supercritical power plant, the operation has the largest contribution to climate change (95% of life cycle impact), particulate matter exposure (60%) and water use (75%). Coal mining, however, stands for the largest contributions to freshwater eutrophication (95%), aquatic toxicity (70%), human toxicity (50%) and land occupation (95%). For a supercritical plant with CCS, the operation contributes 70% to the life-cycle water use, 65% to greenhouse gas emissions, 60% to particulate matter formation, and 50% to human toxicity. Coal mining is most important for eutrophication, land occupation, and aquatic toxicity.

3.2 Natural gas combined cycle

The application of NGCC has grown recently reflecting the abundance of shale gas and the desire to address air pollution [2]. NGCC power plants have higher NO_x emissions than coal-fired plants, which is reflected in their higher terrestrial acidification potential. NO_x emissions also contribute to particulate matter formation and marine eutrophication. For freshwater eutrophication and land occupation, in particular, NGCC's impact are much lower than coal power, but they are also lower for toxicity and climate change. CCS reduces GHG emissions from NGCC by 50-60%, but increases all other environmental impacts by 20-80%. As Figure S2 shows, the most important contributors to environmental impacts of the NGCC with CCS are the extraction and refining of the gas(for land occupation, climate change, freshwater ecotoxicity, human toxicity, particulate matter, and water use) and the construction of the power plant (for eutrophication). The operation of the power plant is the second most important contributor to all impact categories, contributing

5-20%. The large importance of natural gas extraction can be traced to the use of a North American gas production process based on the fossil fuel production inventories of Burnham et al. [56] implemented in this work. Analyses based on European fuel mixes [57] generally arrive at a lower contribution of fuel supply. One significant factor is the difference in methane leakage reported in different world regions [28]. In our assessment, leakage rates in North America have received more scientific attention and at least partly based on measurements while those in other regions are largely based on emission factors reflecting engineering estimates and hence less reliable.

3.3 Hydropower

Hydropower is currently the most important source of renewable electricity, providing 6.1% of total global energy supply and growing at 3% per year. The environmental and social impacts of hydropower have received much attention [58, 59]. Hydropower plants can cause a wide range of potential geomorphological and ecological impacts, including habitat change due to changes in the flow regime, flooding of the reservoir area, reduced sediment and nutrient flow to flood plains, and the obstruction of migration routes. These impacts are heavily dependent on site and project characteristics and commonly not assessed in LCA. Habitat changes threaten species adapted to fluvial environments. Some of the impacts can be mitigated through appropriate flow management regimes or technical adaptations (e.g., fish ladders, environmental flow regimes).

The material and energy required to build hydropower plants are also site-specific. Both reservoir volume and head of a hydropower plant can vary by orders of magnitude. Unfortunately, the available literature is limited use given that inventory data is often not reported. A statistical analysis of 26 cases indicates a factor 2 variance among similar power plants in terms of key inventory items [60]. The life cycle inventories used in this study were based on two planned reservoir hydropower plants in Chile that have a lower land use and therefore produce less biogenic

GHG emissions than the global average [61]. The remote location of one of the plants leads to substantial impacts connected to construction and transport. The impact profiles of these two plants are quite different, as

Figure 1 shows, but impact are generally lower than those of the 2010 global mix of electricity [46], with the exception of land use and metal depletion. Figure S3 shows that the reservoir is the dominant cause of land use, while transportation, including the transport infrastructure, is the most important cause for other impact categories. For these other categories, the reservoir and dam construction are the second most important cause of impacts.

3.4 Wind power

Over the past ten years, installed wind power capacity grew at an average rate of 22% per year. Most of current installed capacity is onshore (98%). As the size of wind power plants has grown and technology has developed further, the capacity factor has grown, leading to lower environmental impacts [62, 63]. Some land or water area is occupied directly by wind turbines, dedicated roads, and other infrastructure. The presence of wind power plants limits the use of a much larger area of land for some purposes, in particular human occupation and habitat for birds and bats [64]. This land, however, can be used for agriculture.

The life-cycle impacts of wind power are one to two orders of magnitude lower than those of coal power for all the assessed impact categories except metal depletion (


a. Coal power

b. Natural gas

c. Hydropower and geothermal

d. Ground-mounted photovoltaics

e. Roof-mounted photovoltaics

f. Concentrating solar power

g. Wind power

h. Geothermal

i. Nuclear

j. Biomass

k. Biomass with CCS*

Legend

Figure 1). It should be noted that the land use indicator results includes area occupied by infrastructure elements of wind farms but does not take into account inter-element spacing. If the total wind farm area is considered, land use would be about two orders of magnitude higher and thus larger than most other power sources apart from biopower and some storage hydro. Offshore systems are more material and energy demanding than onshore, but on the other hand, benefit from more favorable capacity factor and lifetime assumptions. Offshore systems cause more acidification, photochemical oxidants, and particulate matter [32]. The relative contribution of components differs between onshore and offshore systems, however, as is evident from Figure S4. Production of wind turbine components contributes 70-90% to all impact indicators for the onshore system but less than 20-50% for the offshore system. The installation, operations and decommissioning activities contribute significantly to the impact of offshore wind power. The contribution of the electrical connections is also larger than for the offshore system.

3.5 Concentrating Solar Power

Concentrating solar power (CSP) systems utilize direct normal irradiation to produce high-temperature heat for electricity generation. Areas particularly suitable for CSP are those with strong sunshine and clear skies. We analyzed the parabolic trough and central receiver technologies. The trough plant is assumed to be wet-cooled and the central receiver dry-cooled. LCA results show that CSP performs well on pollution-related indicators but has a higher metal use than fossil power [23]. For land occupation, CSP and global mix are comparable. The area occupied by CSP plants typically cannot be combined with larger wildlife or other human uses, but CSP plants may provide valuable habitat for smaller animals and various plants and may be used for grazing. The collector system, which includes the mirrored surfaces used to concentrate direct solar radiation, causes in the order 40-50% of total impact for the central receiver and 30-

40% for the trough for most impact categories (Figure S5). The trough plant uses a synthetic oil heat transfer fluid combined with molten salt heat storage while the central receiver plant uses salt as both as a heat transfer fluid and as heat storage medium and hence does not have a separate heat transfer fluid system. Much less salt is used in the central receiver plant compared with trough, which in large part explains the lower relative contributions from thermal energy storage for the central receiver. Results are sensitive to specific plant designs, which may vary considerably depending site-specific circumstances and project design.

3.6 Photovoltaics

There are a number of viable, substitutable technologies that can provide photovoltaic (PV) power. We have analyzed polycrystalline silicon (Poly-Si) produced in China, by collecting original life cycle data, as well as cadmium telluride (CdTe) and copper indium gallium selenide (CIGS) thin film panel produced in the United States[34]. PV has low impacts on climate change, particulates, toxicity, photochemical oxidant and acidification and eutrophication relative to the current global mix. However, PV requires more metals, especially copper[65]. The impacts of ground-mounted and roof-mounted systems are similar, but different elements contribute (Figure S6). Roof-mounted systems have a smaller contribution from the construction and balance of system. CdTe and CIGS show lower environmental impacts than poly-Si. Energy use during module manufacture contributes most to climate change, particulates and toxicity results. Poly-Si requires more electricity and has higher direct emissions during the production of metallurgical grade silicon, wafers, and modules. Manufacturing in China contributes negatively due to both a lower efficiency and a dirtier energy mix than in Western countries. Hence, for Poly-Si, the contribution of the module manufacturing is higher, while for CIGS and CdTe, transformers, wiring, and mounting are relatively more important.

3.7 Nuclear

Both for the boiling water reactor and the pressurized water reactor, most of the environmental impacts are caused by the extraction and the production of fuel elements. The mining, transportation, refining and handling of fuel elements contribute 64% to 97% of all environmental impacts assessed except for the impact on land occupation, which is mostly caused by the infrastructure (Figure S7). Due to a lack of hindsight on the existing power plants' end-of-life, there is high uncertainty linked to the impacts of the decommissioning phase. According to [66], dismantling assumptions can influence widely the life cycle environmental impact of nuclear power, namely the energy-intensive component removal and the end of life treatment of nuclear waste. Dealing with the legacy of nuclear waste was not assessed here.

3.8 Biopower

The range of technologies falling under the term "biopower" is wide. We modelled here a combined heat and power (CHP) plant, with and without CCS, coupled with two types of feedstocks, energy crops and forest residues. For the sake of proper coverage, the feedstocks considered in our inventories are a variety of short rotation woody crops (SRWC)[40, 67], and forest residues [38]. The CO_2 emissions from land use are not accounted for in the inventories. Without carbon capture and storage, the life cycle greenhouse gas emissions of the biopower plants modelled here range from 28 to 194 g CO_2 eq./kWh (respectively, which is low compared to fossil-fueled power plants, even equipped with CCS) (Figure S8). Producing electricity from biomass with CCS (BECCS) would therefore generate negative net emissions in all our various scenarios. For SRWC, diesel combustion in vehicles and machinery contributes most strongly to particulate matter, photochemical oxidant formation and eutrophication, while the production of various fertilizers contributes most to human toxicity and freshwater ecotoxicity. The main discrepancy with the global mix of 2010 occurs for land occupation, which can increase fortyfold for each kWh provided to the grid.

3.9 Geothermal

The geothermal plant assessed in this study has a high load factor and a very long assumed lifetime [68]. As a consequence, emissions from the production phase are relatively low. However, direct emissions are at least one order of magnitude higher than indirect emissions regarding greenhouse gas emissions, toxicity, particulate matter emissions, photochemical ozone formation, and acidification (Figure S9). This is due to the high geogenic emissions: 83 g CO_2/kWh [69], 0.1587 g SO_2/kWh [70], 0.75 g CH_4/kWh, 0.06 g NH_3/kWh [71] and 4 g Hg/MWh [72]. These assumptions can be considered conservative (especially for human toxicity and freshwater ecotoxicity, for which the characterization factor of mercury is one of the highest across all substances), as most of the environmental impacts are caused by direct site-specific emissions from the geothermal fluid during the plant operation [73].

3.10 Comparison of life cycle greenhouse gas emissions

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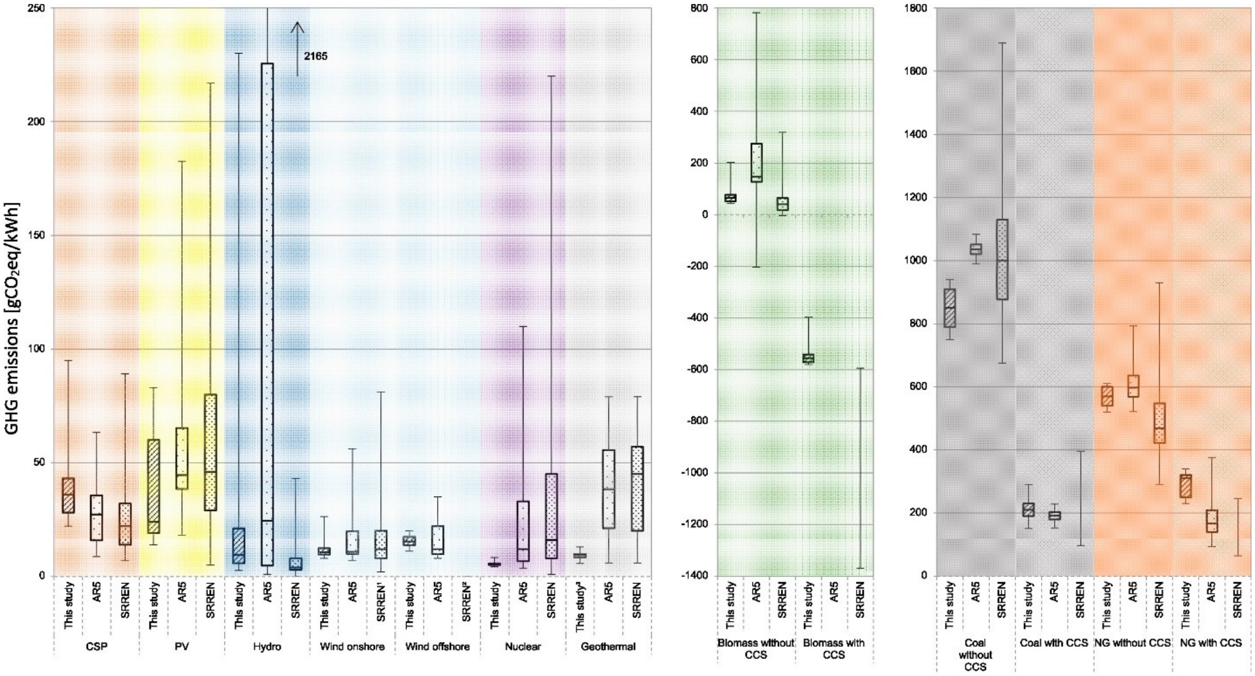

Figure 2, we compare the results obtained in this study with those reported in the literature, as reviewed for the IPCC [10]. For the results of this study, we report the variability among the nine different world regions and the specific technologies assessed here. For CSP, for example, the differences are to a significant degree the result of differences in insolation between the most and least sunny regions of the world, Middle East and Africa, and Economies in Transition, respectively. For coal, ranges reflect both differences in technologies and differences in emissions from mining, while for natural gas, our results range agrees with the literature except for CCS-equipped plants where the energy penalty brings the natural gas plant we modelled to the upper range of the literature. For coal, ranges reflect both differences in technologies and differences in emissions from mining, while for natural gas, the range reflects methane emissions and efficiency assumptions. For hydropower, the wide range of methane emissions from reservoirs reported in the literature is reflected in the IPCC AR5 numbers, but not the work reported in this study, which did not consider those highly emitting plants as viable options for the future. There are no systematic differences between the GHG emissions produced in this report and those reported by

the literature. The lesson of the harmonization studies is that literature studies differ widely through cases, assumptions, system boundary choices, and background[11, 74]. Our work relies on more consistent assumptions on allocation and system boundaries, and the same background data. For some technologies, such as CSP, our calculations represent a wider range of conditions compared to a limited literature, while for other technologies with more case studies in the literature, such as hydropower and bioenergy, we have not been able to study as wide a range of conditions.

4 Discussion

The method presented here ensures the thoroughness of systems covered, and can yield a variety of results that compare with existing literature surveys, even by analyzing a limited set of life cycle inventories. To a certain extent, this method saves the LCA practitioner from building specific inventories for a region or a year, and instead, takes into account various regional and time contexts, according to preset scenarios. Influential regional parameters, such as climatic conditions (wind, direct normal insolation, feedstock yield…) can be hardcoded in the model background, so that inventories are regionalized as late as possible in the impact assessment process. The approach is thus similar to what life cycle harmonization studies have applied retroactively to existing literature, but systematically executed.

Improvements to the present inventories and impact assessment methods can improve the reliability of results. For the inventory, further work is recommended in particular for hydropower (a larger number of plants covered and development of model to estimate inventories given specific site characteristics), nuclear power (more complete inventories also considering the services required), bioenergy (a wider range of different feedstocks and conversion technologies) and fossil fuels (investigation of methane leakage in other continents). For all technologies, models to better estimate the environmental costs and benefits of waste treatment and recycling assuming future conditions of material manufacturing would be beneficial. For impact assessment, metal depletion factors for all relevant scarce metals would be desirable, as would be improvements in the assessments of eutrophication taking all eutrophying substances into account. Further, we note that there is a time horizon issue, where assumptions of the inventory modelling are not congruent with the impact assessment. Inventories report the long-term release of substances leaked from landfills, while impact assessment methods often have a much shorter time horizon. There is a need to harmonize the treatment of the fate of substances across impact assessment and inventory analysis. Lastly, LCA does not take accidents into account. Research on the effects of accidents has largely occurred in parallel and not been integrated into LCA[75, 76]. For some technologies, the consequences of accidents may be as large as those of routine operations, for example for nuclear power[77]. Efforts to integrate the implication of accidents are hence welcome [76].

5 Conclusions

The results of this work show that power technologies not involving combustion have lower environmental impacts for practically all impact categories. CCS increases impacts apart from greenhouse gas emissions. Material requirements are higher for low-carbon technologies, especially solar and wind, than their fossil-fueled counterparts, but related work shows that the demand remains within reasonable limits [23]. Bioenergy has pollution-related impacts that are comparable to the present electricity mix, much higher land occupation, but brings the potential for carbon-negative energy production when CO_2 capture and storage is employed.

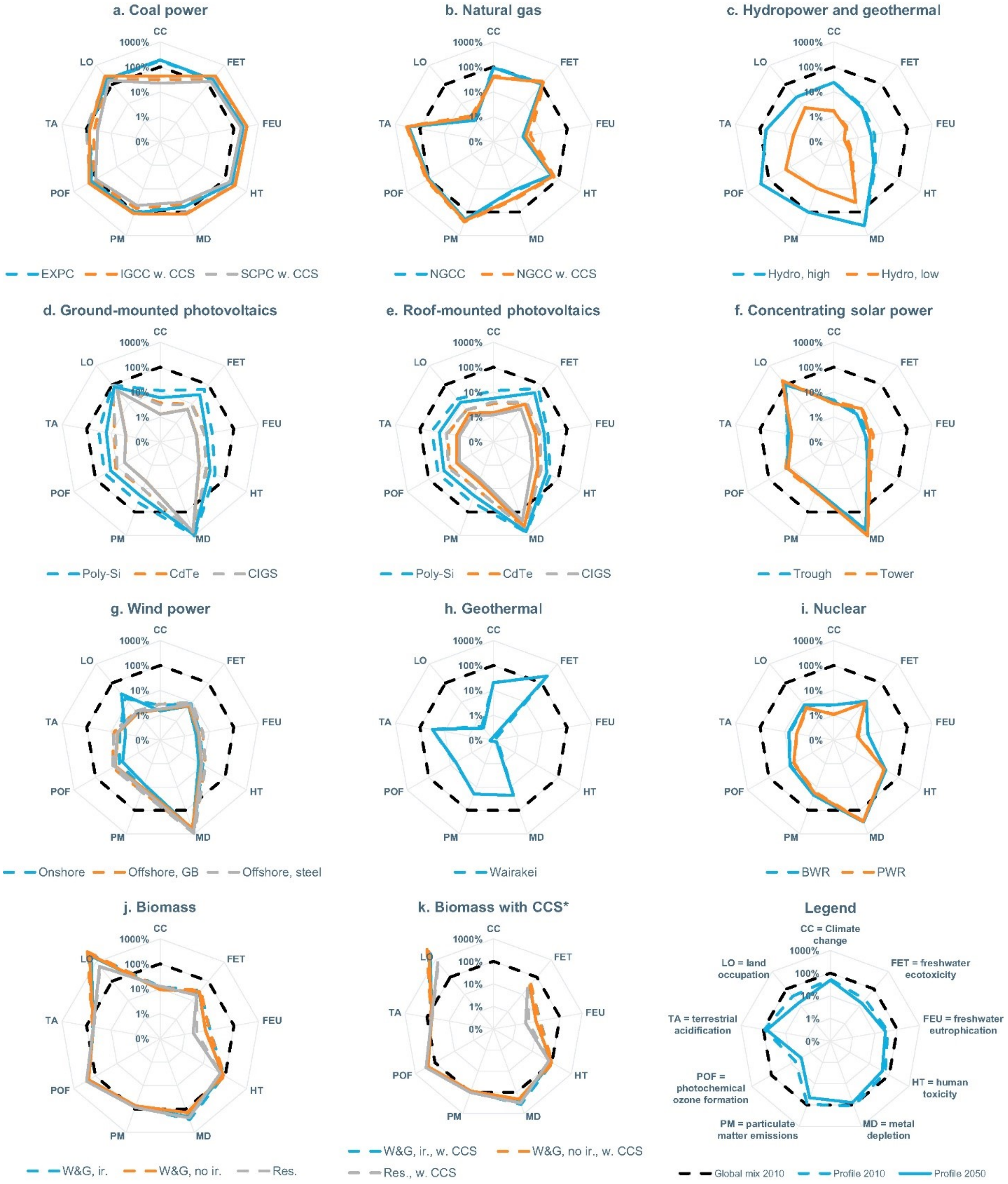

Figure 1: Radar charts of environmental impacts of different types of power plants compared to the current global average power mix. *Biomass with CCS shows net negative greenhouse gas emissions, not shown on the logarithmic chart, the results range from -107% to -122% of the 2010 global electricity mix. EXPC: existing (subcritical) pulverized coal, IGCC: integrated combined cycle, SCPC: supercritical pulverized coal, NGCC: natural gas combined cycle, Poly-Si: polycrystalline silicon, CdTe: cadmium telluride thin-film, CIGS: copper indium gallium selenide, GB: gravity-based (concrete) foundation, BWR: boiling water reactor, PWR: pressurized water reactor, W&G: wood and grass, ir.: irrigation, Res.: forest residue.

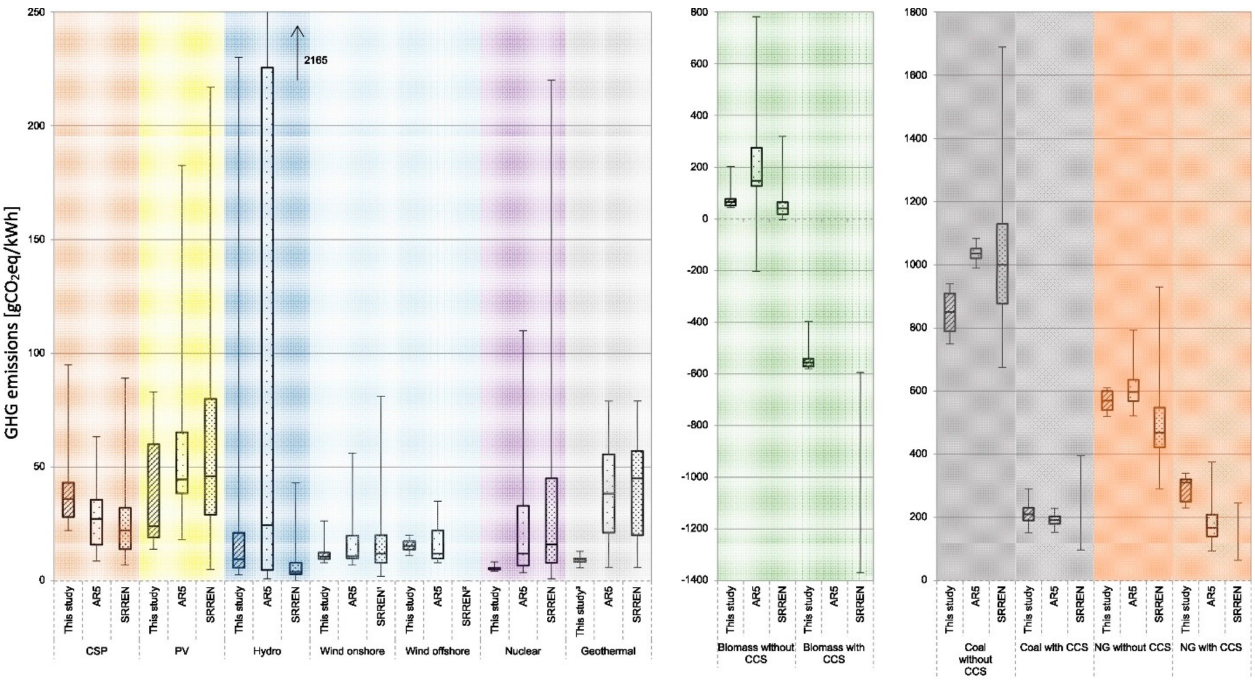

Figure 2: Comparison of life cycle greenhouse gas emissions (g CO_2 eq./kWh) between this study's results, the IPCC Fifth Assessment Report (AR5)[1], and Special Report on Renewable Energy Sources and Climate Change Mitigation (SRREN)[3, 8]. Low-carbon electricity production technologies are shown in the left panel, fossil electricity production on the right panel. The range provided in this study reflects different regions and specific technologies (e.g., for PV, we assessed roof mounted and ground mounted CdTe, CIGS and Poly-Si technologies). The IPCC SRREN presented the range of values reported in the literature, which reflect differences in technologies, sites, and product processes, but also differences in LCA practice such as system boundaries, allocation mechanisms, scope and other assumptions. The IPCC AR5 presented harmonized literature values, where some assumptions were harmonized in an effort lead by the US National Renewable Energy Laboratory (NREL)[11]. CSP: concentrating solar power, PV: photovoltaics, CCS: carbon dioxide capture and storage. Notes: [1]Includes both onshore and offshore results [2]Aggregated to the onshore results [3]One plant, indirect emissions only.

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