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# 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.

## 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

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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 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 5$^{th}$ 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 [76].

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 [41]; 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 [42]. 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 [15,43]. 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 [44], 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