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Thomas Gibon

Doctoral Thesis

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Scenario-based life cycle assessment methods to inform climate change mitigation

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Thesis for the degree of Philosophiae Doctor

Trondheim, October 2017

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PREFACE

Βουλεύου μὲν βραδέως, ἐπιτέλει δὲ ταχέως τὰ δόξαντα.
Be slow in deliberation, but be prompt to carry out your resolves.
Isocrates, To Demonicus, ca. 400 B.C.

Human societies are developing at an unprecedented rate. We have spread to a point that the sheer magnitude of our impact on Earth has now led scientists to suggest a new name for the geological epoch in which we are currently living: the Anthropocene. Each major decision that nations make, domestically or internationally, have enormous consequences on resources, biodiversity, human health, and the environment. As population, affluence, pollution levels, and resource use grow, there is less and less room for trial and error in our quest towards a sustainable way of life on "spaceship Earth." Thorough, well-documented scientific *due diligence* and deliberation are required to support the decisions and resolves of today, that would in turn lead to the prompt implementation of sustainable policies.

Undeniably, technology has been a blessing. It has allowed humanity to achieve many of its wildest dreams. First world countries' citizens live a lifestyle unimaginable to their own great-grandparents: to travel or to communicate across the world in no time, or to have access to once-luxury amenities or food, to name a few perks. In the early 21st century paradigm, ubiquitous technology however feeds off cheap, and often fossil, energy. The overwhelming consensus is now that societies cannot keep affording energy the way we want it, mostly by burning coal, gas and oil; not only because of the eventual depletion of resources, but more urgently because of the soaring rate of greenhouse gas emissions from their combustion.

Ever since Charles David Keeling started measuring meticulously atmospheric CO_2 levels in Mauna Loa in 1958, climate change has never ceased to attract focus, and deservedly so: climate change mitigation is now a priority on every government's agenda. To acknowledge a problem is an important step forward, but perhaps more importantly is to design a sound, detailed, and long-term solution. In December of 2015, 195 governments signed what is now known as the “Paris Agreement,” which obliges them to frame legally binding climate policies aiming at keeping global warming below 2°C. As of September 2017, 160 states have ratified the agreement, including the US (although intending on leaving), China and India. If followed, mitigation scenarios suggest a profound change in the very way we extract materials, manufacture products, provide services, and consume. Exploring the various facets of such a change for the global electricity production sector, as well as identifying and quantifying its consequences for humans and their environment has been the focus of this work.

This thesis is submitted to the Norwegian University of Science and Technology (NTNU) for the partial fulfilment of the requirements for the degree of Philosophiæ Doctor. This work was carried out at the Industrial Ecology Programme, Department of Energy and Process Engineering, in the period from December 2011 to November 2016, under the supervision of Prof. Edgar G. Hertwich and co-supervision of Prof. Anders Hammer Strømman. The research presented in this thesis was funded by the Research Council of Norway through contracts 206998 and 209697.

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Primary publications

I. Gibon, T.; Wood, R.; Arvesen, A.; Bergesen, J. D.; Suh, S.; Hertwich, E. G. A Methodology for Integrated, Multiregional Life Cycle Assessment Scenarios under Large-Scale Technological Change. *Environ. Sci. Technol.* **2015**, *49*(18): 11218-11226.

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Author contribution: research co-design, method and tool development, data collection, data analysis, writing.

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IV. Gibon, T.; Arvesen, A., Hertwich, E. G. Life cycle assessment demonstrates environmental co-benefits and trade-offs of low-carbon electricity supply options, *Renew. Sust. Energ. Rev.*, **2017**, 76: 1283-1290.

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i. Bergesen, J. D.; Heath, G. A.; Gibon, T.; Suh, S. Thin-Film Photovoltaic Power Generation Offers Decreasing Greenhouse Gas Emissions and Increasing Environmental Co-benefits in the Long Term. *Environ. Sci. Technol.* **2014**, *48*(16): 9834-9843.

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   Author contribution: research co-design, method and tool development.

iii. Beucker, S.; Bergesen, J. D.; Gibon, T. Building Energy Management Systems: Global Potentials and Environmental Implications of Deployment. *J. Ind. Ecol.* **2015**, *20*(2): 223-233.

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iv. IPCC (2014) Climate Change 2014: Mitigation of Climate Change, in *Fifth Assessment Report, Working Group III Report, Chapter 7: Energy Systems.* Contributing author, section 7.9.2.

   URL: https://www.ipcc.ch/pdf/assessment-report/ar5/wg3/ipcc_wg3_ar5_chapter7.pdf

   Author contribution: data collection, data analysis.

v. UNEP International Resource Panel, *Green Energy Choices: The Benefits, Risks and Trade-Offs of Low-Carbon technologies for Electricity Production*, Report of the International Resource Panel. Eds.: Hertwich, E. G.; Gibon, T.; Suh., S; Aloisi de Larderel, J. Nairobi: United Nations Environment Programme **2015.**

   URL: http://www.unep.org/resourcepanel/KnowledgeResources/AssessmentAreasReports/EnvironmentalImpacts/tabid/133331/Default.aspx

   Author contribution: research co-design, method and tool development, data collection, data analysis for all chapters, as well as writing for chapters 1, 2, 10.

vi. Martínez Corona, J. I.; Gibon, T.; Hertwich, E. G.; Parra-Saldívar, R. Hybrid life cycle assessment of a geothermal plant: From physical to monetary inventory accounting. *J. Clean. Prod.*, **2017**, 142: 2509-2523.

   DOI: http://dx.doi.org/10.1016/j.jclepro.2016.11.024

   Author contribution: research co-design, method and tool development, writing.

Posters

a. Gibon, T.; Hertwich, E. G.; Bouman, E. A.; Bergesen, J. D.; Suh, S.; Wood, R. Impact assessment methods of energy scenarios for climate mitigation. Presented at the *International Society for Ecological Economics* **2014** conference in Reykjavík, Iceland. **Award for best student poster**.

b. Gibon, T.; Verones, F.; Hertwich, E. G. Making data-intensive life cycle frameworks policy-relevant. Presented at the *International Society for Industrial Ecology* **2015** conference in Guildford, Surrey, UK. **2nd place award for best student poster.**

Structure of papers

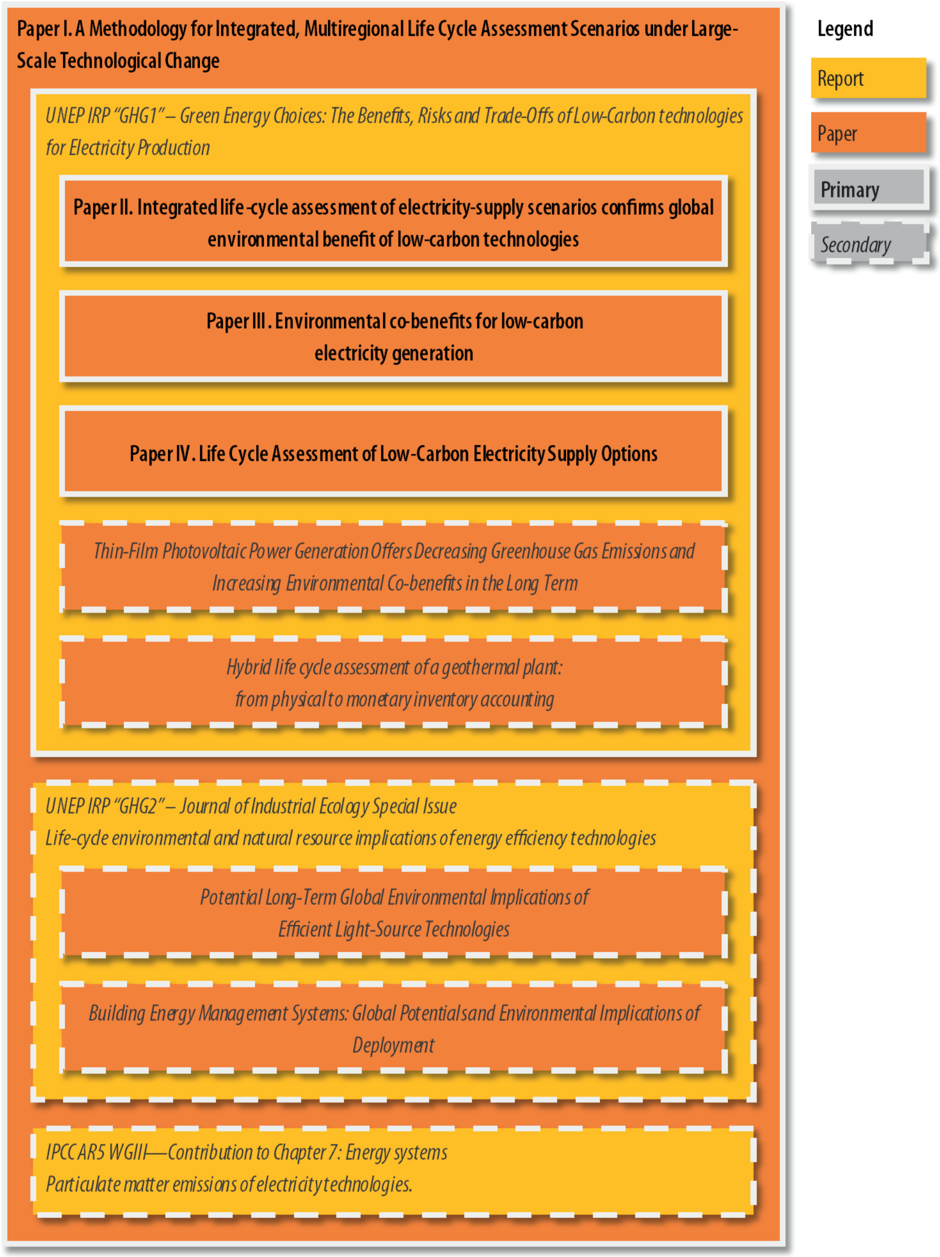

Figure 1. Organization of the work produced during the thesis, posters excluded.

ABSTRACT

Assessing the health and environmental implications of climate change mitigation, and the shift in electricity production technologies in particular, requires the proper consideration of technological and regional specificities of global energy systems, as well as their interactions with each other. Additionally, it is crucial to quantify all kinds of impacts that their fast and widespread rollout will generate in the upcoming decades, this to ensure that energy policies will not lead to more problems than they try to solve.

With the help of a multiregional, hybrid life cycle assessment (LCA) framework, we have evaluated the health, resource, and environmental costs and co-benefits of a transition to a global low-carbon electricity system. The model built for that purpose, THEMIS (for "technology hybridized environmental-economic model with integrated scenarios"), represents the global economy (based on a multiregional input-output table) and technosphere (based on a process life cycle database) in nine regions, and three years (2010, 2030, 2050) along two scenarios. THEMIS allows practitioners to perform impact assessments of a given system from a single life cycle inventory applied to any region/year/scenario combination. Region-specific assessment is particularly necessary for low-carbon technologies whose performance relies on local climatic conditions.

Methodological advances introduced in THEMIS show how deeply energy systems are related to each other. The implementation of integrated hybrid input-output highlights an important kind of feedback effect: production of low-carbon systems will decarbonize the economy in which they are produced, which will in turn decrease the carbon intensity of domestic production. Based on this assessment, we posit that the most successful energy policies will consider regional specificities, feedback effects, and co-benefits.

SAMMENDRAG

Vurdering av helse- og miljømessige konsekvenser av klimatiltak generelt, og teknologiskiftet innenfor elektrisitetsproduksjon spesielt, krever riktig behandling av teknologiske og regionale særtrekk ved globale energisystemer, samt deres samspill med hverandre. I tillegg er det viktig å kvantifisere alle typer konsekvenser som en hurtig og omfattende utrulling av ny energiteknologi vil generere i de kommende tiårene, for å sikre at energipolitikk ikke vil føre til større problemer enn det prøver å løse.

Ved hjelp av et rammeverk basert på multiregional hybrid kryssløpsanalyse (IO) og livsløpsanalyse (LCA), har vi vurdert helse-, ressurs- og miljøkostnader, samt dobbeltfordelene (eng. co-benefits) av energiovergangen. Modellen bygget for dette formålet, THEMIS ("teknologi-hybridisert miljøøkonomisk modell med integrerte scenarier"), representerer den globale økonomien (basert på den multiregionale kryssløpstabellen, eng. multiregional input-output table) og teknosfæren (basert på en livssyklus-prosessdatabase) for ni regioner og tre år (2010, 2030, 2050) langs to ulike scenarier. THEMIS tillater brukere å utføre konsekvensutredninger av et gitt system ved å knytte et enkelt livsløpsregnskap til en hvilken som helst kombinasjon av region/år/scenario. Region-spesifikke vurderinger er særlig viktige for lavkarbonteknologier der ytelsen avhenger av lokale klimatiske forhold.

Metodologiske fremskritt introdusert i THEMIS viser hvor dypt energisystemer er relatert til hverandre. Implementering av et integrert hybrid kryssløpsrammeverk understreker en viktig form for tilbakeslagseffekt: produksjon av lav-karbons energisystemer vil dekarbonisere økonomien der de er produsert, noe som igjen vil redusere karbonintensiteten i innenlandsk produksjon. Basert på denne vurderingen, hevder vi at den mest vellykkede energipolitikk vil vurdere regionale særtrekk, tilbakekoblingseffekter, og dobbeltfordeler.

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First and foremost, my sincerest gratitude goes to Prof. Edgar Hertwich who first believed that I could spend the last few years in a doctoral programme, and who offered me the inestimable opportunity to contribute to the world of international research with this thesis. I am highly indebted to Edgar for his relentless support throughout the years, his intelligence in envisioning where to direct my research, as well as his capacity in always reassessing it, all of which while keeping his modesty as a researcher. He showed me that continuous challenge, steadfast determination, and pride in one's work are a researcher's core values. I will keep striving to adopt this attitude fully in my future career. I would like to thank Prof. Richard Wood for his availability and methodological guidance in the early phase of the thesis, Prof. Anders Hammer Strømman, as well as the other professors from the Industrial Ecology Programme at NTNU (hereafter "IndEcol") for keeping the group's professional and social standards at the highest level.

I also want to express my appreciation to Edgar and the UNEP International Resource Panel secretariat, members and partners, for trusting me in being a main participant to the *Green Energy Choices* project, and particularly to Prof. Sangwon Suh and Joe Bergesen who welcomed me in Santa Barbara for a couple of weeks. It was a great honour to work with such professionals; and I want to thank my other co-authors of Paper II from around the world: Garvin Heath, Andrea Ramírez, Mabel Vega and Shi Lei.

The work carried out in this thesis would not have been possible without the substantial contribution of my IndEcol colleagues Evert Bouman and Anders Arvesen; both of you deserve my deepest gratitude for dealing with poorly written scripts and lack of data quality management. Thank you, Francesca and Bhawna, for your contribution to Paper III. Most naturally, the rest of IndEcol has also played a very important role in my life for the best of the last ten years, and the amount of persons I should thank, either co-workers or friends (most often both) is too high to be listed here – yet I can try. From my first Norwegian stay: thank you Kjartan for your wits and levelheadedness, Christine for your dry humour, Stefan, Guillaume, Carine for enticing me to come back to Trondheim a second time. To my "co-doctorate" friends, it was wonderful to have you around to share the scary PhD experience: Helen, Gibrán, Diana, Magnus, Jo-Kristian, Moana, Linda, Tuva, John, Martin, Carl, Sarah, as well as Dan, Konstantin, non-IndEcolers Alice and Jake. If I forgot you, I know you who will be reasonable enough to understand the social minefield that is the writing of this acknowledgement section. Tusen takk for meg!

The last paragraph goes to the ones closest to me. To my earliest supporters first: thanks to my parents and to François for their unconditional care. Merci à vous de m'avoir soutenu malgré la distance. Last but not least, I would like to thank Alya for her constant encouragement to help me push through the times when my motivation was lacking. You have helped me so much in so many ways, and for that, I am enormously grateful.

1 INTRODUCTION

1.1 Climate change

The rapid increase of greenhouse gas (GHG) concentrations in the Earth's atmosphere is causing deep changes to global and local natural systems. Our most fragile natural systems have already undergone irreversible changes. To cite just two of the most visible examples: polar glaciers are melting because of the mean temperatures rising, and the Great Barrier Reef is dying because of the oceans acidifying. It is without any doubt that we can affirm today that human activities are the root cause of this brutal augmentation of atmospheric GHG concentrations, through the unleashed combustion of fossil fuels as a main source of energy (Intergovernmental Panel on Climate Change 2014). In this respect, profound modifications of our global, energy-producing systems are needed to curb anthropogenic GHG emissions, mitigate climate change, and avoid disastrous environmental and social consequences.

The Intergovernmental Panel on Climate Change (IPCC) advises to limit the average global surface temperature increase to 2 °C over the pre-industrial conditions. In 2012, this increase for the globally-averaged, combined land and ocean surface was 0.85 °C (IPCC 2014a). According to the IPCC, climate change mitigation is a "human intervention to reduce the sources or enhance the sinks of greenhouse gases." (IPCC 2014b) This broad definition reflects the diversity of options available to achieve that purpose: decarbonisation of the global economy, CO_2 capture and storage, or efficiency improvement both at the industrial and demand levels. The development of mitigation policies can therefore address any factor of the Kaya identity[1], by proposing measures that would be reducing either:

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[1] Named after Japanese economist Yoichi Kaya, the Kaya identity summarizes the relationship between anthropogenic CO_2 emissions on one hand (F), and population (P), GDP per capita ($g = G/P$), energy intensity ($e = E/G$), and the CO_2 emissions (more generally, the GHG emissions, and other impacts) per unit of energy ($f = F/E$) on the other hand: $F = P \times g \times e \times f$ (Kaya and Yokobori 1997). The equation is a specific formulation of the IPAT identity and has since been the cornerstone of every IPCC assessment report,

population, affluence (consumption and economic growth), the energy intensity of the economy, or the carbon intensity of energy. The ultimate impact of human activities on the environment is indeed the result of these four factors, and reducing each of those would directly decrease the impact by the same percentage, *ceteris paribus*. However, population and global GDP are not expected to decrease any time soon, and the energy and carbon intensity factors (i.e. what we roughly coin "technology") have to bear the daunting onus of hampering greenhouse gas emissions.

The present thesis addresses the two last components of the identity, carbon intensity, and to a lesser extent, energy intensity. The rate at which anthropogenic greenhouse gas are emitted has increased from 1.3% per year in 1970–2000 to 2.2% in the period 2000–2010, to reach 49 Gt CO_2 eq./yr in 2010, as seen in Figure 2. At this pace, to keep global warming below 2 °C is becoming increasingly challenging, even by implementing *net negative emission* measures after 2050 (Peters et al. 2013). Until 2050, most mitigation scenarios rely on the large-scale and rapid deployment of so-called *low-carbon* energy technologies, emitting less carbon dioxide than their conventional fossil fuel power generation counterparts do. These encompass renewable technologies (whose energy carriers are replenished faster than they are consumed), fossil fuels with carbon capture and storage, and nuclear energy.

1.2 Energy, fossil fuels, and environmental impacts

From the ancestral manmade fires used for heating, cooking, and lighting, to the experimental nuclear fusion reactors of the 21st century, energy has always been the engine of human activities. Thermodynamically speaking, energy is a physical change, meaning that it can never be "produced" *sensu stricto*, only converted. Energy comes in different forms – kinetic, potential, mechanical, electric, nuclear, magnetic, etc. – that can be used in combination or after conversion from one to another in a plethora of industrial applications. The electric form of energy is

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and of global mitigation policymaking (Section 3.1 in Intergovernmental Panel on Climate Change (2000)).

particularly convenient as it allows long-distance distribution without substantial loss, it is scalable, and easily convertible to heat (e.g. using resistors) or work (e.g. using engines). Energy conversion is omnipresent in human activities, and it has actually been observed that energy use explains economic growth in a much better way than the two classical factors of production, capital and labour, do (Stern 2011; Ayres and Voudouris 2014; Giraud and Kahraman 2014). As of 2014, more than 80% of the global primary energy supply consists of fossil fuels (International Energy Agency 2015). As such, energy conversion and supply is the main cause of greenhouse gas emissions; in particular, electricity generation represents 25% of the anthropogenic greenhouse gas emissions in 2010, and 47% of the global 10 Gt C increase from 2000 to 2010. The unbridled use of fossil fuels since the industrial era has contributed singlehandedly to increasing the global warming potential of our atmosphere by releasing the products of their combustion. Perhaps more worrisome, the IPCC reports that the "increased use of coal relative to other energy sources has reversed the long-standing trend of gradual decarbonisation of the world's energy supply" (IPCC 2014b), coal combustion alone eclipsed the entirety of global mitigation efforts. This indicates clearly that phasing out coal combustion (or at least capturing the greenhouse gas emissions thereof) is, or should be, the top priority in global policy, and one of the most significant parameters in energy scenarios.

A large-scale deployment of low-carbon energy supply, together with a reduction of energy demand, appears to be necessary to achieve a shift that would keep global warming below 2°C. Furthermore, this deployment needs to occur urgently; any fossil-fired power plant built today (without carbon dioxide capturing equipment) will only further jeopardize the world's capability to reach current climate targets. The many greenhouse gas-reducing options available to society range over a wide spectrum of mitigation potential and economic costs. In general, most end-use efficiency improvement measures come at a negative cost (i.e. with economic co-benefits), while a global energy transition requires massive investments (see Figure 3), in monetary and material terms. Societies simply cannot afford a second energy transition after the upcoming one, at least fossil-based, either environmentally or even economically.

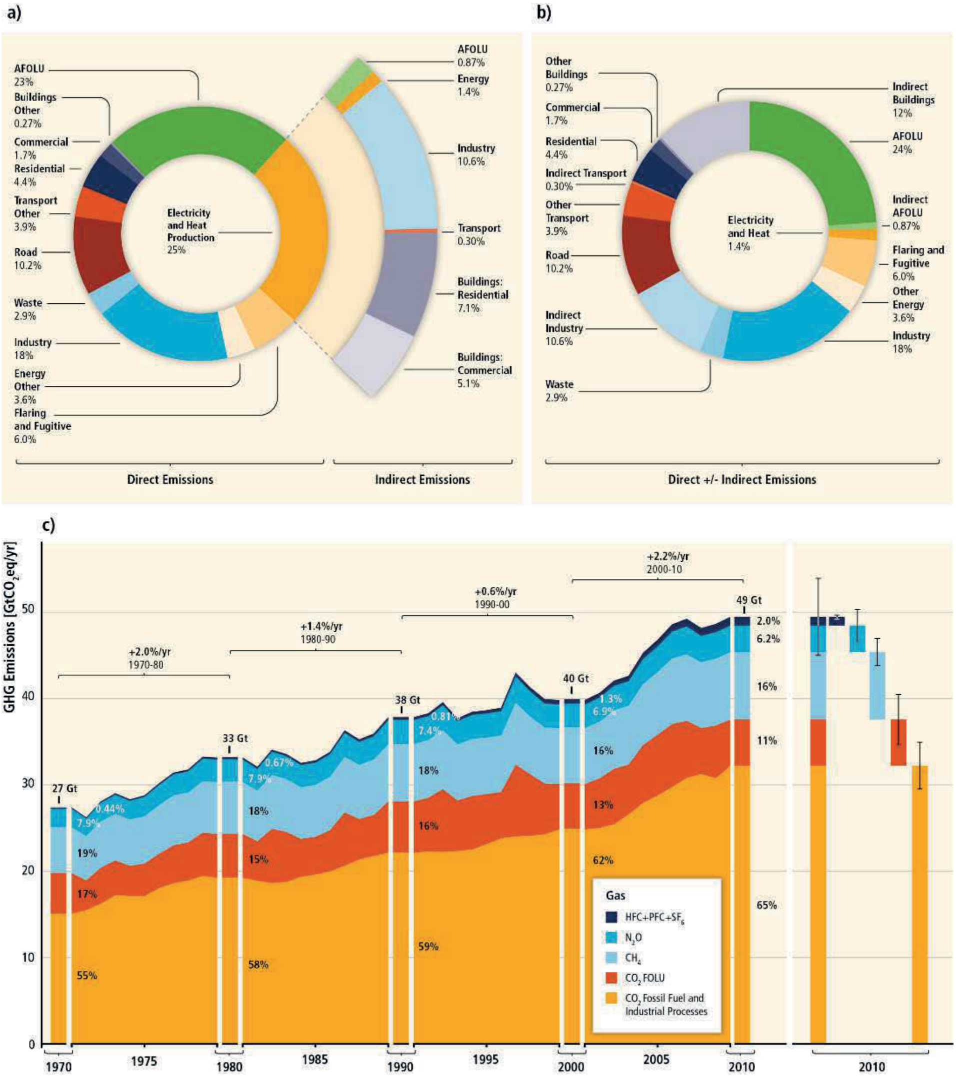

Figure 2. Electricity mix and greenhouse gas emissions.a) Allocation of total GHG emissions in 2010 (49.5 Gt CO_2 eq/yr) across industrial sectors. Electricity and heat production contributes the most. b) Allocation of the same total emissions to reveal how each sector's total increases or decreases when adjusted for indirect emissions. c) Total annual anthropogenic greenhouse gas emissions (Gt CO_2 eq./yr) by group of gases 1970–2010, along with associated uncertainties (whiskers). From IPCC (2014b).

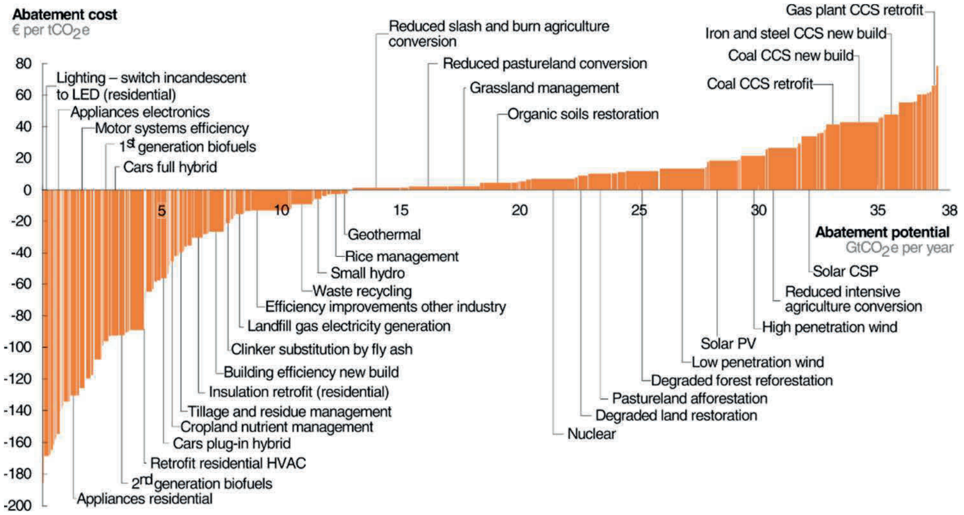

Figure 3. Global GHG abatement cost curve beyond a business-as-usual scenario in 2030. Adapted from McKinsey & Company (2010).

With the large-scale deployment of a technology appears its *learning curve* (or *experience curve*): the observation that each doubling of the installed capacity will reduce the cost of installation by a fixed rate, mainly through process improvement and economy of scale mechanisms. Photovoltaics have for example followed their own “Moore’s law” (in which the reduction is correlated with time rather than capacity) quite faithfully for the past 50 years; the cost of the installed kilowatt of solar panels has been decreasing by roughly 10% a year since the 1970s (Farmer and Lafond 2016). Furthermore, some technologies undergo fast efficiency improvements. To take the example of photovoltaics again, this phenomenon is well illustrated by the National Renewable Energy Laboratory of the United States’ (NREL) efficiency chart plotting the maximum efficiency attained for each photovoltaic technology, continuously updated[2]. Of course, these constant efficiency improvements are also a factor of cost reduction, entertaining the learning curve. These effects are taken into account in the scenarios from the International Energy Agency (IEA) used in this thesis.

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[2] Latest update available at http://www.nrel.gov/ncpv/images/efficiency_chart.jpg

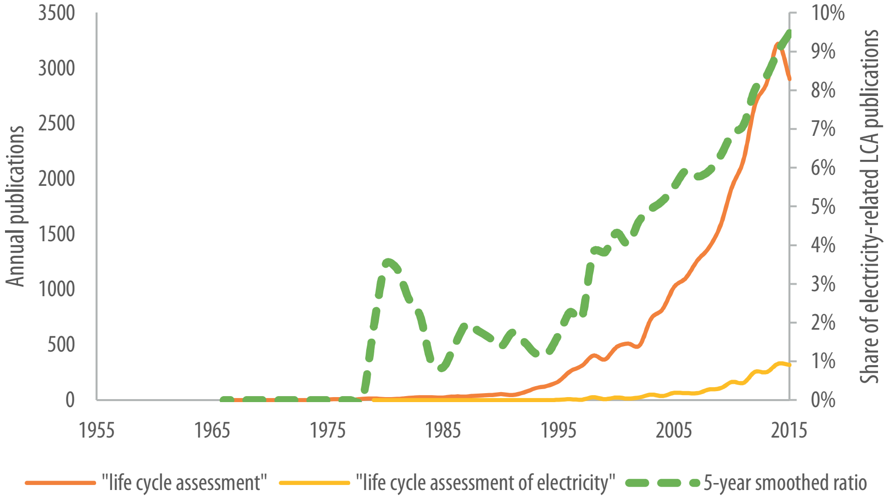

Figure 4. Published electricity-related LCA studies, comparison with the whole body of LCA literature. Source: Scopus, total results for the queries “life cycle assessment” and “life cycle assessment of electricity”, and the 5-year average ratio of annual results, as of early 2016.

Archetypal of the climate-energy-resource conundrum, fossil fuels have attracted the attention of life cycle assessment practitioners, especially since the emergence of fossil-free and low-carbon options for stationary power generation. The diversification of commercially available options indeed offers great opportunities for energy planning, to which environmental assessments may be of great relevance as decision-support tools. Life cycle assessment is also an adequate way to compare fossil and renewable electricity generation on a fair basis, since most impacts occur during the use phase for the former, and the production phase for the latter. Unsurprisingly, the 2005-2015 decade has seen a boom in electricity-related environmental assessment, particularly life cycle assessment (LCA), publications in academic journals. As seen in Figure 4, LCA studies of electricity systems (or related, including grid, storage, efficiency…) represented about 4 in 100 LCA publications in 2005, up to almost 1 in 10 in 2015. This rise in interest for the assessment of electricity systems has been accompanied by an increase in available life cycle inventory (LCI) data, as well as inevitable discrepancies across primary data, adapted data, and results made available in the recent literature. To remediate the disparity of data, detrimental to the studies’ comparability, harmonization efforts have recently been undertaken. NREL has carried out a major harmonization project of published studies of renewable energy (Heath et al. 2014), summarised in a 2012 special issue of the *Journal of Industrial Ecology* (Lifset 2012). Life cycle assessment studies often vary in the characteristics of analysed technologies, and the method they employ to compute results. Harmonisation (and more specifically *meta-analyses*) aims at streamlining these characteristics and methods to bring coherency in the growing pool of LCA results, allowing for comparison and decision support in a policy-making context. It is partly with these streamlining challenges in mind that the work presented here has been carried out.

1.3 Main research questions

This thesis relies on the idea that an environmental due diligence study of a low carbon technology rollout is necessary before any decision is made regarding climate change mitigation strategies. The urgent decisions that governments need to make must be informed, and the scale of these decisions may lead to substantial unforeseen consequences, mostly in environmental and health terms. A potential environmental problem shifting, both along the value chain and across impact categories can be addressed by methods based on a life cycle approach. Another issue, or more of a corollary to the due diligence question, is to understand how to bundle co-benefits in energy policies: is there a way we can optimise policies in order to address not only climate mitigation, but also air pollution mitigation, or the preservation of land and ecosystems? Photovoltaics are the archetypal successful renewable technology, for which deployment is soaring globally, but do we really know how specific metals can be recycled or the type of land solar fields will occupy? Similarly, wind power farms require the extraction, production, and transportation of a large amount of cement and steel before they can produce their first kilowatt-hour of electricity, but is it worth it if turbines are replaced after a mere 20 years? In other words, how can governments achieve efficiency and cost-effectiveness from a limited economical and time budget while addressing a maximum number of environmental problems simultaneously? Energy transition is specifically of concern; the portfolio of electricity-producing technologies available to compose the future global energy mix offers many possible variants. Capturing the environmental consequences of energy scenarios is a key to identify these best variants, since it is the only way to achieve an energy transition with co-benefits – but how can it be carried out efficiently? In particular:

- Energy scenarios are currently not based on a life cycle approach, yet most renewable energy technologies' environmental impacts do not occur during the use phase. Scenarios also account for best-available technologies only and do not consider their performances' variation over time. These characteristics jeopardize their robustness and policy-relevance. *How can energy and climate scenarios be refined and completed to include life cycle, time, and regional aspects?*
- The life cycle literature abounds with high quality studies of low-carbon technologies, but systems are most often assessed in a very particular time and regional context. As mentioned in the introduction, notable efforts have been made in harmonising these studies, but only a full integration of various technologies into a single framework could capture potential feedback effects (among them, and to or from the changing economy within which they are deployed). *How can large-scale environmental impacts of the energy transition be assessed in a consistent and thorough manner?*
- The paradox of (a) assessing a high number of technologies in various contexts consistently while (b) offering a summarised set of policy recommendations is a daunting challenge. The issue of co-benefits quantification naturally appears as a corollary to the previous research question: admitting that the thorough quantification of the environmental consequences of climate mitigation policies is feasible, *is there enough data to inform co-benefit policies? In more general terms, what interpretation of these assessments can be made, and how do they fit, into a policy context?*

1.4 Structure of thesis

This thesis is structured as follows. Section 1 lays out the main concepts of life cycle assessment, and describes the methods used in this thesis. Section 1 is the main course in this thesis, and leads the reader through the various steps of the work carried out to address the overarching research questions. In particular, Section 3 describes the methodological elaboration of an integrated framework to assess the environmental impacts of climate change mitigation (Paper I, Section 3.1), the application of this framework to current energy scenarios and the presentation of the results obtained (Paper II, Section 3.2), a focus on the communication of these results to policymakers (Paper III, Section 3.3), and the full set of comparative results (Paper IV, Section 3.4). Finally, a summary and outlook, containing a set of conclusions and further recommendations based on the outcomes of this thesis can be found in Section 1.

2 LIFE CYCLE ASSESSMENT

2.1 Background

When Kenneth E. Boulding published "Economics of the Coming Spaceship Earth," he conceptualised the fact that Earth's resources were limited and the risks that it poses for an ever-growing industrial society. To that end, he described the necessary shift from what he referred to as a "cow-boy economy" – an economy relying on the carefree and unrestricted use of resources, to what he called a "spaceman economy" – in which resource and energy use, as well as pollution, need to be controlled (Boulding 1966). Control implies measurement; he therefore simultaneously made evident the need for an accountability system, which could quantify resource and energy use, and pollution levels, from industrial activities.

Guinée et al. (2011) give an account of early life cycle assessment (LCA) studies published in the 1970s, originally focusing on energy analysis, and later including the main elements found in current LCAs: resource requirements (materials, energy…), or environmental pressure (emissions, waste generation, land use…). The original purpose of these early studies was mainly product comparison (Boustead 1974; Hunt et al. 1974). Accounting for so many flows, the concepts of system boundaries and value chain became increasingly important. As LCA became a tool for decision-support and communication in proactive companies, setting international standards became necessary (Guinée et al. 1993); the first set of ISO 14040 norms was published in the late 1990s (International Organization for Standardization 1997).

The holistic characteristics of LCA are, interestingly, well-illustrated in the following definition of industrial ecology: "Industrial ecology is the study of the flows of materials and energy in industrial and consumer activities, of the effects of these flows on the environment, and of the influences of economic, political, regulatory, and social factors on the flow, use, and transformation of resources." (White 1994). Life cycle assessment is indeed nothing but a systematic accounting method for inventorying and summarising all the flows of materials, energy, emissions, land, waste, etc. occurring within the boundaries of a system defined according to the demand of one, or a set of, product(s) or service(s). Robert White's definition has come to be more and more fitting for LCA, as the tool is now used not only for product comparison, but also for policy analysis (Wardenaar et al. 2012), scenario analysis, social assessment (SLCA), life cycle management, eco-design (Polster et al. 1996), environmental product declaration (Schau and Fet 2008), water footprinting (Jefferies et al. 2012), farming systems (Nemecek and Kägi 2007), etc. LCA has proven to be a reliable tool to assess the environmental impact of these various systems, but its widespread practice may also be attributed to its standardisation, increasing institutional recognition, and to the fact that process life cycle inventories databases and software have become more widely available (Frischknecht et al. 2005). However, as of 2017, a consensual standard LCA framework is still far from being established. Despite the standardisation of the basic LCA principles two decades ago (International Organization for Standardization 1997), progress keeps being made and questions keeps being debated on several fronts: methodology (e.g. should all LCAs be consequential? account for uncertainty?), data management (e.g. how to maintain life cycle inventory or characterisation databases efficiently?), or policy-relevance (e.g. what indicators are to be used to support decisions?).

2.2 Basic algebra

Roughly said, LCA is a method for summing and multiplying physical quantities in order to aggregate large datasets into a limited list of environmental "scores," or indicators. As simple addition and multiplication are involved, a main assumption in LCA is linearity: if producing one kilogram of steel at the steel mill is assumed to emit two kilograms of carbon dioxide, then producing ten kilograms of steel will emit twenty kilograms of CO_2. This assumption substantially simplifies LCA calculations, at the cost of robustness in scalability. This will not be addressed in this chapter as LCA in its strictest form is neither intended nor equipped for addressing non-linear behaviours – for various strategies to overcome the issue of linearity, see de Haes et al. (2004). Since most LCA practitioners treat large datasets linearly, linear matrix algebra is therefore as a tool of choice to compute life cycle assessment calculations.

The robustness of a life cycle assessment also mainly lies in the exhaustiveness and quality of the data gathered about the *product system* in question, during the so-called *inventory analysis* phase. After defining the *goal and scope* of the study, by agreeing on a sound functional unit, inventory analysis is a meticulous process of compiling data from various sources. This stage establishes the matrices: Z, containing the total amount of the various flows exchanged between the system processes; x, the vector of total output of these processes; A, the normalised *technology matrix*; F, the factor, or *stressor matrix*, and y, the *demand vector*. The relationships between those variables is described in the following equations.

$$Z = A\hat{x} \Leftrightarrow A = Z\hat{x}^{-1} \tag{1}$$

Where the circumflex denotes the diagonalisation of a vector. Introducing the external final demand, the mass balance becomes equation 2.

$$Ax + y = x \tag{2}$$

Where Ax is the interindustry output tied to the upstream production of the total output x, and y the final demand. Rearranging, and under the condition that A is square we introduce the Leontief inverse L, in equation 3.

$$x = (I - A)^{-1}y = Ly \tag{3}$$

Each column j of the Leontief inverse matrix L_{*j} describes the quantity of various inputs from the system's processes necessary to supply one unit of final demand of product j. Simply put, the total output vector is a linear combination of these columns, as shown in equation 4:

$$x = \sum_{j} y_j \, L_{*j} \tag{4}$$

The next stage is the aggregation of this data into environmental impact quantities, or *life cycle impact assessment* (LCIA), based on various characterisation factors that depend on the LCIA methodology selected. A matrix containing such characterisation factors, C, is introduced to calculate a handful of indicators reflecting various environmental impact categories. To obtain the vector of environmental impacts, d, we multiply C with the vector of stressors and emissions, e, as demonstrated in equations 5 and 6.

$$e = Fx \tag{5}$$

$$d = Ce = CFx = CF(I-A)^{-1}y \tag{6}$$

It is possible to disaggregate d to perform a contribution analysis, in various ways, as shown in equations 7, 8 and 9.

$$D_{pro,cons} = CF(I-A)^{-1}\hat{y} \tag{7}$$

$$D_{pro,prod} = CF\hat{x} = CF\widehat{(I-A)^{-1}y} \tag{8}$$

$$D_{str} = C\hat{e} = C\widehat{Fx} = CF\widehat{(I-A)^{-1}y} \tag{9}$$

Where:

- $D_{pro,cons}$ is a *imp* × *pro* matrix containing the environmental impacts caused by each final demand process, i.e. at the consumption level (eq. 7), e.g. used to calculate multipliers and footprints;
- $D_{pro,prod}$ is a *imp* × *pro* matrix containing the environmental impacts caused by each total output process, i.e. at the production level (eq. 8), e.g. used to calculate territorial emissions;
- D_{str} is a *imp* × *str* matrix containing the environmental impacts caused by each stressor (eq. 9), e.g. used to calculate stressor contribution analyses.

It is also possible to track the embodied emissions or impacts along a product's value chain, combining production- and consumption-based approaches, as described in eq. 10 using the example of global warming potential (GWP).

$$D_{pro,GWP} = \widehat{C_{GWP}}F(I-A)^{-1}\hat{y} \tag{10}$$

Where $D_{pro,GWP}$ is a *pro* × *pro* matrix containing all the embodied flows of greenhouse gases throughout the system boundaries, and C_{GWP} is the vector of GWP characterisation factors. The result can be plotted as a Sankey diagram, such as the one shown in Figure 5. In this figure, only foreground processes are shown as destination nodes, since the final demand equals zero for all other (background) processes. More details are available in Paper I.

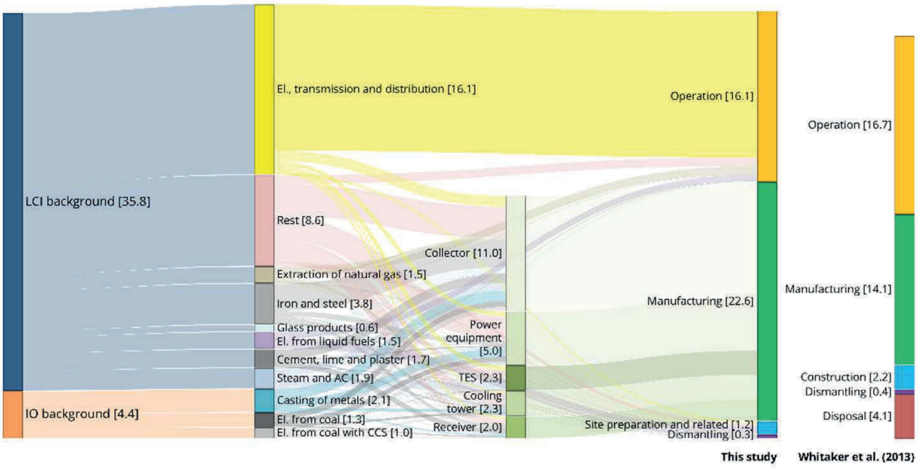

Figure 5. Sankey diagram of embodied GHG flows within the boundaries of a concentrating solar power plant system, modelled with hybrid LCA, and compared with the same inventory, non-hybridised (from Paper I).

2.3 Hybrid life cycle assessment

The expression “Hybrid life cycle assessment” usually denotes an assessment method combining LCA and IO analysis. This method is interesting because LCA and IO largely complete each other in terms of data: process-based LCA is detailed enough to offer a degree of resolution unattainable with IO tables, whereas IO databases, sourced from national statistical bureaus’ data, allow a coverage of the whole economy, inherently solving the system boundary problem (mentioned in Section 2.1). This combination also overcomes lack of life cycle inventory data for certain sectors on which traditional LCA does not focus. Examples of omitted processes in LCI databases mostly include services: insurance or banking, or office infrastructure and project overheads, whereas industrial processes are usually well detailed (Majeau-Bettez et al. 2011). On the other hand, supply and use tables do not provide information that is sufficiently detailed to be able to distinguish various systems or processes belonging to a same economic sector. Moreover, transactions are principally accounted for in monetary units. It is important to note that this issue is not systemic; rather, it is due to the data limitations of current LCI databases. Similarly, physical IO tables (PIOTs, tables where transactions are accounted for in physical units) exist, and given enough data gathering efforts, could theoretically be as detailed as needed. One tends to remark that, in fact, LCA and IO analysis are very closely related in methodology, as probably best illustrated by the use of the "Leontief inverse" in Section 2.2[3]. Linear algebra is used in both disciplines, and even concepts that seem to pertain exclusively to one domain or the other (e.g. allocation in LCA or constructs in IO) happen to share the same underlying mathematical principles (Majeau-Bettez et al. 2014).

In hybrid LCA, various levels of integration exist. The most straightforward way to carry out an analysis is the *input-output based* analysis, or the practice of primarily using the economic sectors to perform the assessment (Suh et al. 2004). By adding a process-based LCI to an IO economic table in a marginal fashion, or completing the LCI with inputs from the IO table to tackle the truncation, one lays the ground for a *tiered-hybrid* analysis (Strømman et al. 2006). The next step towards a more complete hybridisation consists in adding downstream flows from the process-based LCI, back to the input-output table, for an *integrated* hybrid LCA (Suh et al. 2004). Other approaches exist, such as *waste input-output* (Nakamura and Kondo 2002; Kondo and Nakamura 2004), an ingenious way to include a physical layer to a monetary input-output table (originally to address the need for accounting for flows with no economic value, i.e. waste in economic terms), or *path exchange* hybrid analysis (Lenzen and Crawford 2009).

The work presented in this thesis makes extensive use of tiered and integrated hybrid LCA, namely by connecting process LCA and multiregional input-output databases. The algebra is fundamentally identical to the elements exposed in the previous section, so that all computations remain valid. The main difference resides in the composition of the A matrix, now containing both process LCA and

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[3] Wassily Leontief earned the 1973 Nobel Memorial Prize in Economic Sciences for his work on input-output tables.

economic information. Perpetuating the notation given in Strømman et al. (2006), we write:

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

Matrices A_{ij} contain coefficients representing the flows or the transactions transiting from i to j, with $\{i,j\} \in \{f,p,n\}^2$, where f refers to the analysed system's foreground, p to the process LCA database, and n to the symmetric input-output table. Throughout the thesis and papers, we assume that matrices $A_{np} = A_{pn} = 0$, as there is no account for interaction between process LCA and input-output backgrounds. The so-called *downstream* matrices (as in "downstream from the analysed system's foreground"), A_{fp} and A_{fn}, also equal the zero matrix in tiered hybrid cases.

In this thesis, hybrid LCA is almost exclusively treated as an extension of process LCA, and as such, mostly input-output coefficient matrices are used. The full interindustry matrix *Z*, as well as the total emissions and factors are used marginally as intermediate calculation steps for aggregation or scaling. Large-scale parameters such as population, GDP growth, or global resources are not accounted for, which justifies the absence of any balancing process after modification of the IO tables. The upscaling of impacts is linearly calculated in proportion to the assumed electricity consumption, which is a parameter exogenous to the model presented in this thesis.

2.4 Life cycle impact assessment

Life cycle impact assessment models as accurately as possible the causal chains related to human activities and their consequences on the environment. These cause-effect chains may be complex. As an example, (local) emissions of CO_2 increase the concentration of CO_2 in the (global) atmosphere, which in turn increase global radiative forcing, which in turn increases global temperature (but with local variations) in the longer term. Consequences of global warming include various radical changes in several cycles of the Earth climate, such as the melting of polar caps, which in turn, again, liberate methane hitherto trapped in the permafrost, or increases the albedo of polar regions, which increases global warming even more, etc. Ultimately, all human activity (consumption, services, industry, mining, transport, agriculture…) has consequences on human and ecosystem health, and resource availability, which are known as areas of protection (at an *endpoint* level). Of course, cause-effect chains are highly complex, toxicity-related ones being an infamous example. Life cycle impact assessment is consequently a very active field, aimed at tackling uncertainties and modelling fate and effect more accurately (Huijbregts et al. 2011; Frischknecht et al. 2016).

The impact assessment step, during which the full life cycle inventory is converted in environmental terms (impacts, damage) is crucial in LCA. Depending on the impact category, it relies on many modelling and perspective assumptions. Impact assessment methods (often called *methodologies*[4], henceforth used) propose sets of characterisation factors. Methodologies commonly used and recognised by LCA practitioners, include, among others: ReCiPe (Goedkoop et al. 2013); Stepwise2006 (Weidema 2009); Impact2002+ (Jolliet et al. 2003); EDIP2003 (Hauschild and Potting 2005); Eco-indicator 99 (Goedkoop and Spriensma 2000); CML 2001 (Guinée 2002); TRACI 2 (Bare 2002); and USEtox (Hauschild et al. 2008). This diversity of methodologies has to do with a few main reasons: the wide range of assumptions and uncertainties inherent to impact assessment models (especially toxicity), the rapid development of these methods, and their purpose.

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[4] According to the Oxford English Dictionary, *methodology* is “the branch of knowledge that deals with method generally or with the methods of a particular discipline or field of study,” yet, in this context, it is widely used to describe a method to derive characterization factors, or a set thereof.

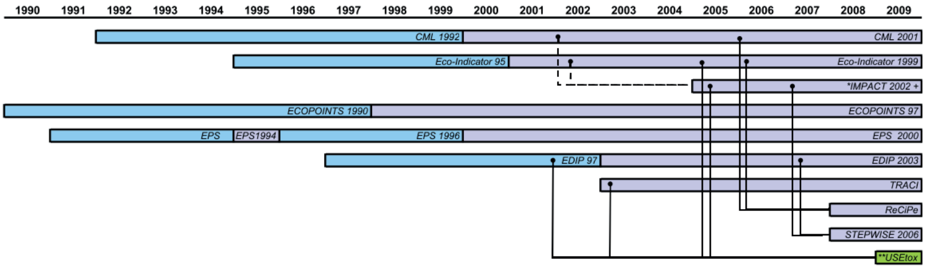

Figure 6. Timeline of LCIA methodologies, including mergings (indicated by the black connectors). From Pizzol et al. (2011).

Some indicators are very well aligned across these methodologies. For example the characterization factors for global warming potential (GWP) do not deviate much as they are all derived from the works of the IPCC (Intergovernmental Panel on Climate Change 2007)[5]. However, an important difference is the way toxicity indicators are designed. Toxicity is regarded as one of the most uncertain indicators due to the wide variety of parameters in the calculations: what toxic substances are covered, for what species or compartment representativeness, what kind of model is used to derive toxic effects, etc. Testing various methodologies for the impact assessment of metals on human health, Pizzol et al. find toxicity results that are varying from each other by orders of magnitude (Pizzol et al. 2011). Unless more is known about a certain stressor (its geographical location, the kind of compartment it is emitted in…), it is challenging to reduce the uncertainty at the characterisation stage. In addition to uncertainty, impact assessment assumptions should be consistent with a goal: is the practitioner comparing short-lived consumption products, mid-term policies, or long-term resource management scenarios? The question of time horizon is crucial for characterisation, since most stressors have cumulative effects sometimes long after their emission.

The methodology used throughout this thesis is ReCiPe (named after the three institutes behind its development, Goedkoop et al. (2013)). The manner in which ReCiPe deals with uncertainties and time horizons is through the adoption of

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[5] The GWP factors can be found at
https://www.ipcc.ch/publications_and_data/ar4/wg1/en/ch2s2-10-2.html

"cultural perspectives", inherited from the introduction of Thompson et al.'s typology of a person's way of life (Thompson et al. 1990) in the Eco-indicator 99 methodology (Goedkoop and Spriensma 2000). ReCiPe retains three perspectives, out of five, from Thompson et al. (1990): individualist (reflecting short-term interest and technological optimism), hierarchist (most common policy principles), and egalitarian (reflecting long-term due diligence and precautionary principles) (Goedkoop et al. 2013). In the context of prospective life cycle assessment of energy scenarios, the hierarchist perspective applies, as a compromise between the rapid development of clean technologies, and the long-term uncertainty associated with current global energy scenarios.

Proposals for single environmental indicators have been numerous, with the main argument that it facilitates results communication, comparisons, and, as a result, more objective decision-making processes (Blanc et al. 2008; Cartelle Barros et al. 2015). Without going as far as testing these proposed environmental scores, the policy-relevance of LCA studies' results and options for meaningful indicators in a policy context is explored in Paper III.

3 INFORMING CLIMATE CHANGE MITIGATION

This section introduces Papers I-IV, which all relate to the environmental consequences of climate change mitigation through the deployment of low-carbon electricity production technologies. Paper I focuses on the development of the model and the database used to carry out the analysis, elaborating on methodological aspects and design choices. Paper II is an application of that model to the large-scale deployment of a set of electricity generation technologies. Paper III offers a further perspective on the communication of these results and their policy-relevance. Paper IV is a comprehensive and more complete comparison of the technologies analysed, with some insight on the specific impacts of each.

The introduction to each paper *n* consists of a rationale (Sections 3.*n*.1), a list of objectives (Sections 3.*n*.2), a brief description of the methods used (Sections 3.*n*.3), a recapitulation of the results (Sections 3.*n*.4), a summary on uncertainty and limitations (Sections 3.*n*.5), and a reflection on the potential impact of the study (Sections 3.*n*.6).

3.1 Paper I: Framework development

3.1.1 RATIONALE

If successfully followed, climate change mitigation roadmaps will lead to profound changes in the way our global economy affects the environment, beyond the reduction of greenhouse gas emissions. Not only are direct emissions of greenhouse gases of products and services expected to decrease, but also indirect emissions. These indirect emissions are highly dependent on the carbon content of the economy in which they are provided, and more particularly of the energy system supplying said economy. It is therefore crucial to be able to assess environmental impacts (including non-climate impacts) in a context accounting for a changing economic and technological background.

Implementing scenarios to a hybrid life cycle assessment framework allows for the long-term prospective assessment of a range of systems. In this exercise, we chose to hybridise electricity generation system inventories with a life cycle inventory database and a multiregional input-output background. By reflecting changes in technological efficiency, electricity mixes, and pollutant emission policies, the model becomes appropriate for assessing an existing or emerging technology under climate change mitigation scenarios.

3.1.2 OBJECTIVES

This study describes the method behind the setup of THEMIS[6], the "technology hybridised environmental-economic model with integrated scenarios." The main goals can be summed up in three points:

a. To lay down the methodological tools to set up a prospective, multiregional, hybridised life cycle assessment model,

b. To single out methodological challenges, such as double-counting, fully integrating energy technologies, or harmonising a heterogeneous set of data sources,

c. To exemplify the use of this new hybrid model by applying the assessment to an emerging electricity generating technology.

3.1.3 METHODS

Integrated hybrid LCA is at the core of the methods used in this paper. The principles followed for the model setup as well as the main methodological challenges encountered (data harmonisation and implementation of scenarios) are described hereafter.

Given the quantity and heterogeneity of the various sources considered, a primary challenge to overcome is to streamline the data. Discrepancies in time,

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[6] In Ancient Greek mythology, Themis (Θέμις) was a Titaness, daughter of Ouranos (the Heavens) and Gaia (the Earth). She personified custom, tradition, divine justice, and civilised existence. She could foresee the future, hence the model's namesake.

technological, or geographical representativeness are indeed recurrent barriers for LCA practitioners. As the energy scenarios drive the whole model, we chose to align the geographical and time resolution to nine main regions of the globe and the 2010–2050 period, respectively.

Three main changes were brought to the databases to represent future years: technological efficiency, energy mix, and emissions regulations. The first change was mainly based on the "New Energy Externalities Developments for Sustainability" or NEEDS, a four-year EU FP6 project aiming at evaluating the "full costs and benefits of energy policies and of future energy systems" (ESU and IFEU 2008). NEEDS' "realistic-optimistic" assumptions were used to modify industrial processes in ecoinvent 2.2. The energy mix scenarios modifications were based on the IEA's two Energy Technology Perspective (ETP) scenarios for nine world regions to 2050. Finally, the global atmospheric emissions of major pollutants were assumed to follow the historic trend of 1990-2011 in the European Union (European Environment Agency 2013). Inherently, making these choices assumes that technological efficiency and emissions restrictions improvements up to 2050 are similar for Europe and the world alike.

3.1.4 RESULTS

The main outcome of this paper is a fully functional hybrid life cycle framework able to compute the environmental impacts of various systems from 2010 to 2050, in nine various global regions, and according to two scenarios. The model using this framework, THEMIS, supports both tiered and integrated hybrid life cycle assessments.

To illustrate the use and interest of THEMIS, the prospective analysis of a concentrated solar power plant is carried out. In 2010 and according to the regional context, life-cycle greenhouse gas emissions for CSP range from 33 to 95 g CO_2 eq./kWh, and falls to 30-87 g CO_2 eq./kWh in 2050. Using regional life cycle data yields insightful results: climate, regional technology, or energy mix

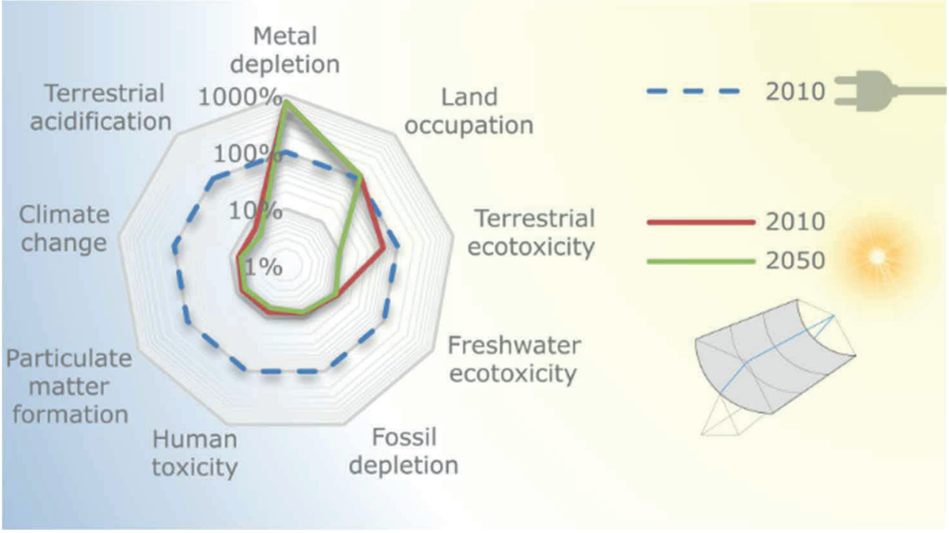

Figure 7. Impacts of concentrated solar power. Comparison of the life cycle environmental impacts of 1 kWh of electricity from a concentrated solar power tower plant in 2010 and 2050 with the impacts of the 2010 global grid.

3.1.5 UNCERTAINTY AND LIMITATIONS

Limitations of this study exist at different levels. First, the compounding uncertainties arising at various stages of the LCA: background data adaptation, life cycle inventory of the foreground system, life cycle impact assessment… are a phenomenon typical to LCA studies (Finnveden et al. 2009). In this study, this is accentuated by the combination of heterogeneous data sources. The results variability is reflected by quantifying the environmental impacts by region and by year, in both scenarios.

The assumptions that the global future economy will undergo the same changes as in Europe have been made for technological efficiency and emissions regulations. Using Europe as a proxy in most of the scenario integration process – which reflects the lack of detailed data for non-European regions – is an assumption that should be kept in mind when analysing and interpreting the results of prospective analyses made with THEMIS.

Beyond the various data sources, we have relied on expert judgment to estimate the penetration of various systems in the future energy markets. These assumptions are not based on actual measurements or scientifically sound predictions, but rather on the informed judgment of the co-authors. Further research should focus on documenting more accurately the deployment of specific systems, based on relevant parameters, such as prices, demand, and proper resource assessment, and if possible rely on dynamic features.

3.1.6 POTENTIAL IMPACT OF STUDY

This novel attempt at combining methods, databases, and scenarios into a single framework reveals both the challenges of and the need for such exercises. Where most previous LCAs are snapshots of a system in a certain time and regional context, the presented framework accounts for all regions and all years considered *by default*. Especially in the context of informing climate change mitigation, an integrated framework like THEMIS can deliver precious insights – most importantly the regional variability of the implementation of a mix of technologies and environmental consequences of global energy policies. It is worth noting that the THEMIS structure is completely independent from the data that the model relies on. Paper I stresses on the links between potential data sources, their degree of complementarity and the issues associated with the various possible combinations. The use of this framework was illustrated with an electricity-producing technology, yet THEMIS can support the assessment of any kind of technology; as a matter of fact, the same structure has been used to assess the environmental consequences of end-use electricity demand efficiency policies in the context of climate change mitigation (Beucker et al. 2015; Bergesen et al. 2016). The framework has also been tested with other databases, such as CEDA (Bergesen et al. 2014), further showing its flexibility. It was also used to analyse the effects of renewable energy penetrating the European market, by Berrill et al. (2016). Papers II-IV, as well as the two UNEP IRP reports on the trade-offs of climate change mitigation (United Nations Environment Programme 2016; Potočnik and Khosla 2016), use THEMIS extensively. It is therefore our hope that similar structures be used in future large-scale hybrid LCA studies.

3.2 Paper II: Interpretation

3.2.1 RATIONALE

Literature is scarce when it comes to describing and quantifying the environmental consequences of climate change mitigation in a consistent way. In particular, the energy sector will have to undergo massive changes, driven by regional policies that mainly base their decisions on economic arguments. For example, the levelised costs of electricity technologies or the implementation of carbon taxes could play a determinant role in steering energy policies one way or another. A consequence of this economic focus is the negligence of the broader picture, of the full "due diligence" of such policies: what is the stress of such a shift on the biosphere? Can society afford deeply changing energy systems with regard to available materials and resources?

On top of that, the life cycle assessment literature abounds with results on specific technologies, often analysed in a specific context and reliant on study-specific assumptions and idiosyncratic choices of method and background inventory data. Comparisons between variants of technologies are often imbued with uncertainty, which weakens the general insights offered by such studies. While harmonisation efforts have been conducted (Hsu et al. 2012; Whitaker et al. 2012; Heath et al. 2014), the lack of a unified assessment framework of electricity production technologies is regrettable still. Here we address this research gap.

3.2.2 OBJECTIVES

In this study, we propose a large-scale integrated assessment of future electricity systems. The main objectives, beyond demonstrating the relevance of integrated hybrid LCA for this type of exercise, are:

a. To harmonise heterogeneous hybrid life cycle data and integrate it in a consistent framework,

b. To quantify the environmental co-effects of climate change mitigation under stringent decarbonisation policies,

c. To identify the main upcoming challenges of the large-scale deployment of low carbon electricity generation, such as land use or material requirements, in a long-term and region-specific way.

d. To set an agenda for future research on the use of life cycle methods for informing climate change mitigation.

3.2.3 METHODS

The main core of the model used consists of THEMIS, the framework laid out in Paper I (Gibon et al. 2015). Principally, we apply the THEMIS framework to a range of electricity producing technology options, which are implemented to the model via the integration of their hybrid inventories. The exhaustive list of electricity-producing technologies is: photovoltaics (cadmium-telluride, copper-indium-gallium-selenide, polycrystalline silicon), concentrated solar power (parabolic trough, central tower), hydropower, wind power (onshore, offshore gravity-based and steel foundations), as well as coal- (subcritical, supercritical, integrated gasification combined cycle), natural gas-fired power plants (combined cycle). The two latter (fossil-fired) power plants are modelled with and without carbon dioxide capture and storage technology.

These technologies are assumed to represent the electricity mix of nine world regions from 2010 to 2050. Their life cycle inventory varies over this period, to represent improvements such as material efficiency (e.g. thinner photovoltaic modules for the same performance), energy efficiency (lower consumption or higher output), or recycling (either assuming recycling at the end-of-life or the use of recycled material at the fabrication stage). The databases used to represent the future economic and technological world is altered to reflect changes in industry efficiency or pollution control (see Paper I for details).

3.2.4 RESULTS

The paper presents the results of a large-scale, multiregional, integrated hybrid analysis of energy scenarios. Two main sets of results are shown: first, a technology comparison per unit generation, and, second, results of scenario modelling.

The technology comparison focuses on the environmental impacts of energy technologies per kilowatt-hour provided to the electricity grid, with various background regions, years, and scenarios. The main finding for this first set is that low-carbon technologies have overall lower pollution-related environmental impacts than their fossil-fuelled counterparts. In addition to emitting greenhouse gases, fossil fuel, principally coal, combustion is indeed the source of a variety of other air pollution issues, such as particulate matter emissions, or photo-oxidant creation. Best available natural gas power plants may offer lower environmental impacts in general than coal-fired power plants, at the cost of higher life-cycle nitrogen oxide emissions. Nevertheless, bulk material requirements are higher for low-carbon technologies, namely for wind and solar power plants. This causes 20% to 50% of these technologies' greenhouse gas emissions. Low-carbon technologies also tend to cause more system- or region-specific impacts than fossil-fuelled technologies: land occupation and natural habitat change depend mainly on the type of system chosen (e.g. ground- vs. roof-mounted for photovoltaics) or the region of implementation (e.g. boreal vs. tropical areas for hydropower, direct normal irradiance (DNI)[7] for all solar technologies).

Scenario results compare the environmental impacts of the IEA Baseline scenario vs. those of the BLUE Map scenario. For both cases, and for the same variety of environmental impacts as in the technology comparison. It mainly highlight the role of coal power in the global future electricity mix, especially without the application of carbon dioxide capture and storage. Following the BLUE Map scenario would lead to lower environmental impacts globally, but higher (yet manageable) requirements of iron and steel, cement, and copper.

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[7] DNI is a measure of the amount of solar radiation at a given place; it is directly dependent on latitude, which represents the angle that the Earth's surface makes with normal sunlight. In fact, the word "climate" itself comes directly from the Ancient Greek *klima* (κλίμα), which literally means "inclination, slope".

3.2.5 UNCERTAINTY AND LIMITATIONS

Uncertainties mentioned in section 3.1, Paper I, are valid for this study: uncertainties embedded in life cycle inventories and adjusted databases, as well as in the assumptions made for future mixes and system market shares. Sensitivity analysis was not performed, following the argument that the parameters tested in the study belong more to a storyline than an actual prediction. Data intensity was also a reason for not addressing the issue. The absence of any kind of uncertainty analysis is obviously a limitation, and the results of the study should be seen as an order-of-magnitude idea of the consequences of low-carbon electricity deployment.

3.2.6 POTENTIAL IMPACT OF STUDY

To the authors' knowledge, the work presented in Paper II is the first attempt at framing and applying a fully integrated hybrid method for the assessment of a set of systems, with the inclusion of long-term scenarios and regional resolution. Paper II is both a proof-of-concept for a new method and a rough estimate of future emissions and material requirements of a low-carbon electricity global society.

3.3 Paper III: Informing policymaking

3.3.1 RATIONALE

It is now certain that enforcing climate change mitigation policies will come with environmental costs and benefits, at every scale (Stechow et al. 2015). So-called "co-benefits" of climate change mitigation encompass all the environmental impact reductions accompanying the application of climate change mitigation policies, for instance the reduction of particulate matter emissions as a result of fossil fuel taxation. Co-benefit analysis is pertinent as the reduction of greenhouse gas emissions, from electricity generation in particular, is a priority on most governments' agendas. Beyond the challenging task of limiting negative effects of the deployment of low-carbon technological solutions, the question whether we should harness this opportunity to kill two (or more) birds with one stone is therefore central. Quantifying these co-benefits has the potential to encourage the implementation of mitigation policies.

Opportunities to address other pollution issues have been identified, quantified from a short-term or regional perspective (Thompson et al. 2014; Cifuentes et al. 2001; Davis 1997), but also from analysing low-carbon electricity deployment on a longer-term horizon (Markandya et al. 2009). These studies do not rely, however, on life cycle data, neither do they cover a wide range of environmental impact or damage; in fact, most of them analyse the co-benefits of climate change mitigation on air quality solely.

Furthermore, covering all available and emerging technologies is essential to comprehend what costs and opportunities arise with low carbon technology development; the panel of technologies assessed in Papers I and II is not complete, and Paper III overcomes this shortcoming by adding biomass and nuclear technologies to the analysis.

3.3.2 OBJECTIVES

This paper aims at adopting a holistic perspective on the environmental performance of stationary electricity generation options in order to quantify the degree of co-benefice of climate change-mitigating energy scenarios, and thus to support policymaking. The main objectives are:

a. To quantify environmental and health impacts of the future global electricity production in a straightforward and consistent fashion, relying on endpoint indicators, easier to interpret than the usual midpoint indicators – which only denote various aspects of the environmental burden of a system on aquatic, terrestrial and atmospheric milieus without offering any insight on actual consequences onto areas of protections,

b. To place and show the relevance of these results in the context of co-benefits analysis, to determine what environmental and health opportunities lie in low-carbon electricity deployment,

c. To integrate a wider panel of technologies by integrating biomass and nuclear technologies.

3.3.3 METHODS

The model developed in Paper I, THEMIS (Gibon et al. 2015) is applied to the set of technologies described in Paper II (Hertwich et al. 2015) extended with biopower technologies, as well as two nuclear power inventories. In addition, endpoint characterisation factors (damage to ecosystem quality and to human health) are included in the framework. For the sake of communicability, midpoint indicators are aggregated into a small set of groups for each endpoint indicator. Selecting a smaller set of indicators while addressing actual damage instead of stress confers policy-relevance to these results by making them clearer, more readable and interpretable (van Hoof et al. 2013). The introduction of biopower technologies in the set of inventories brings along site-specificity issues. Yield assumptions directly influence land occupation results, yet yield is a highly variable parameter that requires fine hydrological and climate modelling.

3.3.4 RESULTS

Results show an overall bettering of the environmental footprint of electricity by shifting to low-carbon generation. Land occupation, however, remains a concern for biopower, with a sensible variation of land use per kWh produced depending on the feedstock. The variety of biomass systems indeed appear to offer the wider range of performances, due to the difference in feedstocks. Using forest residues as feedstock yields the lowest impacts, even “negative damage” to ecosystem and human health when used with carbon capture and storage. However, short-rotation crop-based biopower could engender the highest impact on ecosystems due to land occupation. Cultivating these crops in the regions with the lowest yields appears to lead to the highest damage on ecosystems per kWh among all variations of all technologies analysed here, but this is merely a consequence of using global characterisation factors. The results shown here should be refined by adopting spatially-explicit coefficients.

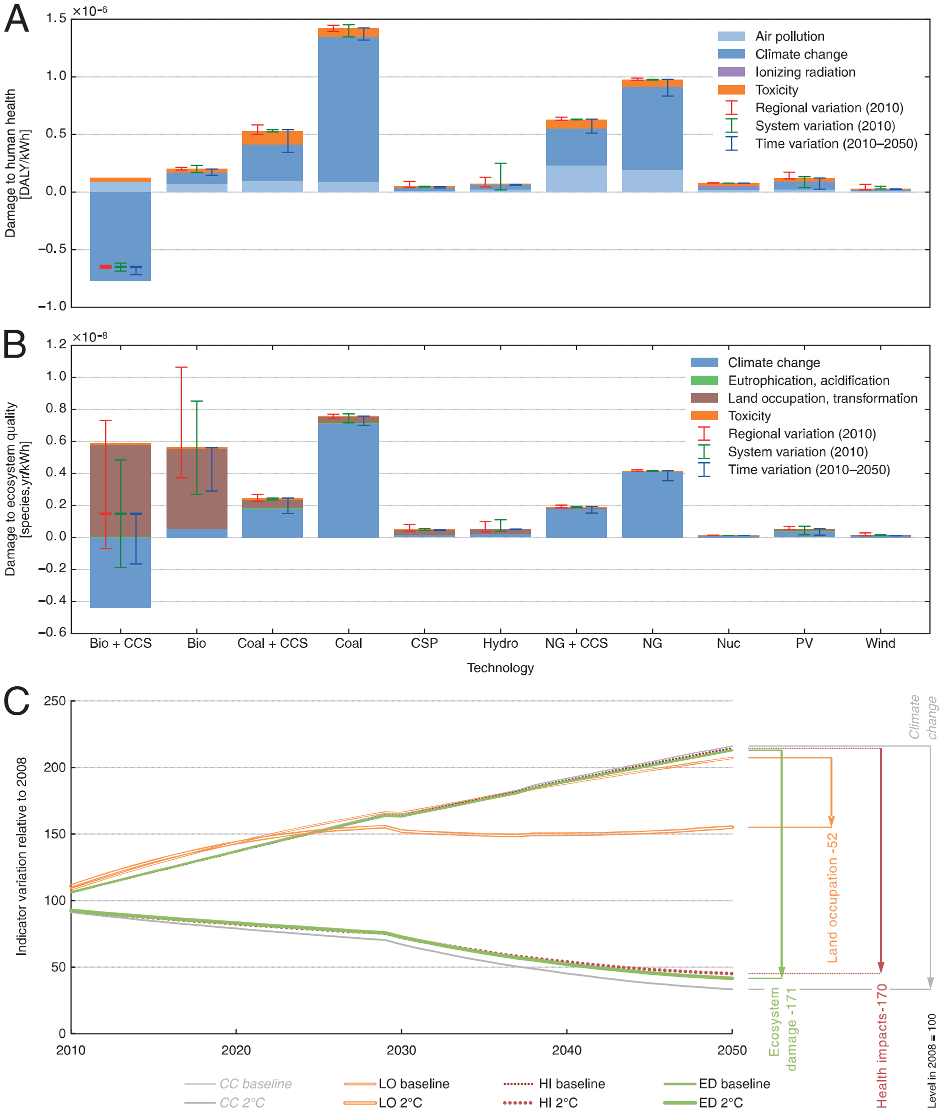

Figure 8. Future impacts of power generation. Panels A and B: Comparison of electricity producing technologies from two endpoint perspectives: A) damage to human health and B) damage to ecosystem quality. Panel C: Variation of the impact of global electricity production on climate change, land occupation, health impacts, and ecosystem damage according to a baseline and a 2°C energy scenarios (respectively “Baseline” and “BLUE Map” scenarios from the International Energy Agency).

3.3.5 UNCERTAINTY AND LIMITATIONS

The aggregation of impacts of different nature and scope into one indicator relies on assumptions that are sometimes remote from quantifiable biophysical mechanisms. For example, the disability-adjusted loss of life years (DALY) indicator depends on subjective assumptions such as the "disability weight," an index that aims at qualifying the degree of gravity of a disability (where 0 is perfect health, 1 is death). One aggregation further in the impact assessment chain therefore introduces substantial subjectivity and uncertainty The characterisation factors used in the midpoint-to-endpoint conversion and aggregation processes rely on regional averages and do not take into account local specificity, let alone time specificity.

3.3.6 POTENTIAL IMPACT OF STUDY

A first conclusion of the work carried out in Paper III can be made at the technology level: with the exception of forest residues-fed gasification plants with carbon dioxide capture and storage, bioenergy for electricity production does not offers a benefit in terms of damage to ecosystems. The ecosystem damage of biomass systems is comparable to conventional fossil fuels, land use being the main issue in these cases. Land use and land use change appear very detrimental to biodiversity. At the power plant project level, biomass deployment should therefore be considered only after a careful environmental assessment of the feedstock supply chain. At the global level, it raises the question of the actual feasibility of planned biomass (with and without CCS) rollout.

Second, the reduction of greenhouse gas emissions from electricity generation is a priority on most governments' agendas, even more so since the Paris Agreement, to be enforced in June 2016. Opportunities to address non-climate pollution issues have been identified, quantified from a short-term perspective (Davis 1997; Cifuentes et al. 2001), and more recently from analysing low-carbon electricity deployment on a longer-term horizon (Markandya et al. 2009). Paper III goes one step further by quantifying the actual direct and indirect damage on human health and ecosystems of a low-carbon energy shift. A recurrent remark has been raised during the several review rounds of the UNEP IRP report I contributed to (United Nations Environment Programme 2016): policymakers need clearer information; the midpoint format does not quite help in making a decisions as to which technology one should invest in to preserve human health and the environment. Although midpoint and endpoint results are consistent, we hope to reach more policymakers using a different set of indicators than in the rest of the thesis.

3.4 Paper IV: Full comparison

3.4.1 RATIONALE

This paper is a scientific follow-up to the UNEP International Resource Panel report: “Green Energy Choices: the benefits, risks and trade-offs of low-carbon technologies for electricity production” (United Nations Environment Programme 2016). The results of the full assessment presented in the UNEP report are shown, as well as a comparison with existing literature. The scope of technologies is the same as in Paper III, i.e. the set presented in the UNEP report, with the addition of nuclear power and biopower.

3.4.2 OBJECTIVES

The objectives of this paper are the actual original objectives of the whole thesis, namely:

a. To compare the environmental impacts of current and emerging power generation technologies on a consistent basis, by systematically accounting for production and operation according to various regions, years and scenarios,

b. To emphasise technology-specific impacts and their causes, especially trade-offs, so as to nuance the environmental profiles of power technologies to deploy in the upcoming years, and highlight the risks and benefits of a global rollout,

c. To contribute to life cycle data availability efforts by publishing inventories and results missing from Paper II.

3.4.3 METHODS

As in Paper III, THEMIS was used to calculate the life cycle impacts of electricity technologies. For that purpose, the foreground of THEMIS was extended to include biopower and nuclear systems, while the geothermal plant was modelled following a tiered hybrid approach, as described in Corona et al. (2016).

3.4.4 RESULTS

Results presented in Paper IV rely on the data gathered for the "Green Energy Choices" report (United Nations Environment Programme 2016) and presents an exhaustive set of midpoint indicator results including additional technologies. A comparison of these results with the results of the LCA reviews in the IPCC's Fifth Assessment Report (AR5) (Intergovernmental Panel on Climate Change 2014) and Special Report on Renewable Energy (Intergovernmental Panel on Climate Change 2011) is also provided.

3.4.5 UNCERTAINTY AND LIMITATIONS

The study does not contain uncertainty analysis, but presents the variation of results across regions and years. The comparison with LCA literature results, namely the observation that each technology's data points do not spread over a range as wide as other studies, shows that variation should also be tested for technological parameters, which largely influence impacts per functional unit.

3.4.6 POTENTIAL IMPACT OF STUDY

With Paper IV, we aim to provide a coherent basis of life cycle assessment results for further comparison. An exhaustive dataset of results and all life cycle inventories are indeed provided for further use. Another goal of this paper was to present an extensive summary of the work carried out in the UNEP IRP report, "Green Energy Choices" (United Nations Environment Programme 2016).

4 SUMMARY AND OUTLOOK

4.1 Conclusions

This thesis aims at providing a clearer environmental picture of key emerging and mature low-carbon options available to supply the world with electricity up to year 2050. Environmental pressures, resource depletion, and energy security require a major shift from the all-fossil paradigm of the twentieth century towards a more sustainable and flexible way of delivering power to the grid. The COP21 agreement was signed to enforce that shift and legally bind governments to enact mitigation policies, among which energy-related tax and subsidy schemes will play a pivotal role.

First, we recall the research questions established in section 1.3 and provide concise answers in the light of the research presented in the thesis. We then focus on the particular electricity technology that have been analysed, detailing the results obtained for each of them. Finally, a last section is dedicated to potential further work and improvements to the life cycle assessment techniques utilised in this thesis.

4.1.1 RESEARCH QUESTIONS

How can energy and climate scenarios be refined and completed to include life cycle, time, and regional aspects?

A main limitation of energy scenarios of the IEA is that only the impacts of operational phases are accounted for in estimates of current and future large-scale environmental consequences of electricity technology deployment. Although “real-life” data availability is limited for emerging technologies, especially end-of-life treatment, for which industrials do not have enough hindsight for data collection, we find that completing operational aspects by extending inventories with production, maintenance, repowering, and end-of-life phases sheds a new light on low-carbon technology deployment. As the most notable example, the production phase of solar and wind technologies proves to be more material-intensive than fossil-fuelled counterparts are. Furthermore, when possible, these inventories were hybridised, and extended with input-output data on non-process inputs, which increases impact by a factor of about 10% (see Figure 5 for a contribution analysis). By default, energy scenarios tend to underestimate emissions and impacts in general, by reducing what should be life cycle impacts to operational impacts only – a drawback that can be tackled by following life cycle assessment guidelines.

Moreover, as technology undergoes steep learning curves, assuming a constant state of a technology in the long term, and of the economy in which this technology is being deployed, is too simplistic. As an illustration, a prospective study of the large-scale deployment of automobiles for the period 1970–2010 would have wound up worthless if energy efficiency and emission reduction measures had been left out of the scope. Adapting life cycle inventories to future years by applying increasing recycling rates, material and energy efficiency, and decarbonisation of the background economy leads to significant reductions compared to business-as-usual assumptions of major energy scenarios.

Finally, matching technology choices and improvements with regions of application matters, as we see that a same technology may double its impact (Paper I, Figure 3). Again, this is generally not applied in main energy scenarios, a flaw that THEMIS could tackle in a systematic manner.

How can large-scale environmental impacts of the energy transition be assessed in a consistent and thorough manner?

Data wise, the use of a single framework integrating all technologies to be assessed, together with background systems, appear to be a viable solution to capture all effects from the system, including various feedbacks. The collection and quality check process is however more cumbersome than gathering life cycle results from the literature; however, it allows for harmonisation and flexibility. Furthermore, consolidating life cycle inventories is only possible when the primary data is available, which highlights the importance of publishing life cycle data systematically, together with metadata.

Large-scale environmental impacts of the energy transition have been assessed by extrapolating single-plant inventories to global deployment levels, including interactions between each other, and characterising their impacts by applying linear coefficients. A main critique of this methodology is that consequential effects have therefore not been properly considered. Therefore, with respect to non-linearity and consequential effects, the research question has not been completely answered. The limitations are discussed in section 4.2.

Is there enough data to inform co-benefit policies? In more general terms, what interpretation of these assessments can be made, and how do they fit, into a policy context?

The question of "right amount of data" (the principle of *parsimony*) is difficult to answer in such a policy-support context. It has been showed that changing the scope of a life cycle assessment, or its characterisation methods, changes its conclusions. Data completeness is surely to strive for, but in the context of this study, where uncertainty is very high (and has not been quantified), only order-of-magnitude effects should be analysed. From this perspective, the conclusions that low carbon technologies bring co-benefits are certain, and so is the observation of material requirement trade-offs, mainly due to lower load factors and shorter lifetimes. This should therefore support policies as long as the accurate quantification of these effects is not necessary.

4.1.2 POWER PRODUCTION

This section summarises the main findings of the thesis regarding individual power production technologies.

Coal

Our profound dependence to coal power has led to most of the global electricity-related CO_2 emissions, while endangering humans and ecosystems due to heavy amounts of particulate matter, ozone-forming substances, or indirect land occupation due to mining. Quantifying the extent of that damage is a necessary process when picking the composition of a future energy mix, the results of which

(Papers II-IV) clearly show that coal power is not only the least judicious option for the climate, but also for air pollution, representing externalities that remain unpaid for. Despite almost all indicators flashing red, coal remains an attractive option for emerging countries, because of the low cost of feedstocks and infrastructure, and the fact that no one is held financially responsible for these externalities. Although the rollout of carbon dioxide capture and storage (CCS) will probably curb greenhouse gas emissions from the coal sector until 2050, it will require a supplement of feedstock ("energy penalty") being extracted, transported and combusted, carrying along its load of environmental pressure. Initiatives such as divesting investment funds from the coal industries, the implementation of a carbon tax, the controlled development of CCS, should be enforced urgently in hopes to not only mitigate climate change from coal combustion, but to limit and reduce the use of coal globally.

Natural gas

Considered as a "bridge fuel" that would support the transition from coal to renewable sources, natural gas can be used to produce power at roughly half the direct GHG emissions of coal power. Paper II shows that, however, even deploying the best available technologies (natural gas combined cycle) would have a significant impact on ecotoxicity and particulate matter emissions, especially when equipped with CCS, due to energy penalty. Perhaps more of a concern, recent studies of fugitive methane emissions at the extraction phase, via unloading and leakage, show that previous studies may have underestimated the amount of methane reaching the atmosphere (Burnham et al. 2012) – which would increase the life cycle GHG emissions of natural gas power. Whether this underestimation is significant or not is still subject to debate (Alvarez et al. 2012).

Nuclear power

Nuclear power technologies, fission in particular, rely on the use of a mineral resource (uranium) which does not replete fast enough for the technologies to be considered renewable. Furthermore, producing power from fission is a long and complicated process that produces waste, and is relatively risky, and renewableadvocating institutes such as IRENA do therefore not support it[8]. Uranium reserves are however abundant and the feedstock supply chain considered clean when compared to its fossil counterparts, which makes nuclear a sui generis technology. In fact, and perhaps counterintuitively, results from Paper III show that, overall, nuclear power generates the least health damage per kWh, with ionising radiation as the main environmental issue.

Hydropower

Hydropower projects are among the most site-specific of the energy system portfolio. Specific parameters that vary largely include their location (latitude and distance from end-user), the configuration of the dam and reservoir, the expected output (the two latter do not correlate), are all hurdles to attaining a reasonable degree of representativeness in life cycle inventories. Project-specific too, direct emissions from the degradation and/or anaerobic digestion of flooded biomass in tropical areas can make the per-kWh greenhouse gas emissions from hydropower soar to more than 2 kg CO_2 eq. in extreme cases. This issue was addressed by Hertwich (2013), who concludes that, with the exception of the reservoir area, no parameter or combination of parameters can predict the biogenic emissions of reservoirs. At a global scale, direct emissions from reservoirs are estimated to amount to about 1 Gt CO_2 eq. per year – and yet the process is still poorly accounted for in national inventories (Deemer et al. 2016).

Wind power

Wind power has undergone a steady increase in global capacity since its early developments. Onshore remains the go-to but we have found that offshore wind farms can cause low environmental impacts too, despite a more carbon-intensive maintenance, compensated by their higher capacity factor. With hydropower and photovoltaics, wind is predicted to be one of the largest renewable electricity supply options of the next decades (REN21 2013). We find that this choice makes

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[8] Reuters, July 2009. Accessed 28.06.2016 at http://gulfnews.com/news/uae/general/irena-will-not-support-nuclear-energy-says-chief-1.480998

sense from the point of view of all environmental impact categories, with the possible exception of potential avian and chiropteran fatalities and high material requirements (steel and copper).

Photovoltaics

The term "photovoltaics" covers many technologies with various performances. We analysed the environmental impacts of polycrystalline silicon, and two thin-film technologies: cadmium-telluride (CdTe), and copper-indium-gallium-selenium (CIGS). Despite high metal requirements, PV technologies show low environmental impacts, with the exception of land occupation in the case of ground-mounted photovoltaics. Decentralised systems are however expected to develop, and roof-mounted panels can be built on land already occupied by buildings. A clear limitation of our study on photovoltaics, however, lies in the fact that many technologies still compete today to become the next standard: multijunction cells can for example provide twice the electricity per square meter that a polycrystalline or thin-film cell can output – they were not included in our study.

Concentrating solar power

According to our assessment results, concentrating solar power technologies appear as material-intensive solutions: copper to connect remote and large plants to the grid, and large amounts of concrete, in the case of tower technologies. As far as operation and maintenance is concerned, the main concern seems to be water. Wet-cooled power plants consume more than dry-cooled ones, but even these requirements are still comparable to those of fossil fuel plants. Thermal storage allows the production of electricity when the irradiance is not sufficient, and can extend the lifetime production of a power plant, therefore reducing the impact of construction per kWh delivered to the grid.

Geothermal

Geothermal power technologies were not broadly assessed in this thesis. Only the case of the Wairakei plant was studied, and added to the set of modelled technologies in Papers III and IV. By its size and technology, the geothermal plant in Wairakei cannot be deemed representative of the majority of geothermal plants and therefore conclusions cannot be drawn directly. The occurrence of toxic direct emissions at the plant (as modelled by Corona et al. (2016)) has been measured to be particularly high at various independent sites. For instance, the amount of mercury found in the steam emissions of the geothermal plants of Lardarello (Baldi 1988), and Mt. Amiata (Bacci et al. 2000), both in Italy, is anomalously high. Arnórsson (2004) reports similar results, together with potential local “scenery spoliation, drying out of hot springs, soil erosion, noise pollution, and chemical pollution of the atmosphere and of surface- and groundwaters”.

Biopower

Biopower plants have only been modelled in Papers III (Gibon et al. 2017b) and IV (Gibon et al. 2017a). Two types of biomass feedstocks were modelled, forest residues and lignocellulosic biomass from short rotation coppice. Various degrees of irrigation and yield assumptions were analysed, resulting in a wide range of potential impacts. In the worse cases analysed in Papers III and IV (short rotation coppice, high inputs and lower yield), agricultural land occupation is found to be the main contributor to ecosystem damage. In these lower-yield cases, ecosystem damage from biomass-fired electricity appear to be higher than that of electricity production from conventional fossil fuels, thus highlighting the potential issues with large-scale biopower deployment. Conventional systems (such as traditional forests) have not been analysed but offer even lower yields, therefore higher potential impacts.

4.1.3 END-USE ENERGY EFFICIENCY

On the far left hand side of the GHG cost abatement curve (Figure 3), energy efficiency measures deserve all the policymakers’ attention. According to the adage among energy efficiency advocates, “the best power plant is the one not built.” End-use energy efficiency technologies have been the focus of a second UNEP IRP report, published as a special issue of the Journal of Industrial Ecology (Potočnik and Khosla 2016; Suh et al. 2016). THEMIS was directly used for several case studies of the special report: lighting (Bergesen et al. 2016), copper production (Kulczycka et al. 2016), transportation (Taptich et al. 2016), and building energy management systems (Beucker et al. 2016).

4.2 Life cycle methods: reflections and further work

This thesis introduces the various aspects, options, and challenges, inherent to the assessment of climate change scenarios. Paper I presents an attempt to build a framework for assessing climate change mitigation policies, focusing on electricity production, and the challenges linked with reconciling inconsistent data sources. Paper II illustrates the use of the hybrid model developed in Paper I, applied to global electricity production, and gives a few conclusions on environmental costs, benefits and trade-offs of energy transition. Pushing interpretation further, Paper III reports an attempt at developing policy-relevant indicators, relying on endpoint characterisation factors. Finally, Paper IV recapitulates the results of the study, with technologies and indicators omitted in other papers, for the sake of full transparency, advocated in this thesis and by industrial ecologists in general.

A general remark that has arisen throughout the thesis is that, even after a few decades of development, environmental impact assessment is still in its infancy, especially concerning analyses with a prospective or site-specific perspective. Evidence includes the variety of sources used to adapt databases to future scenarios, or the regrettable absence of uncertainty analysis. There is much to say about the various ways environmental impact assessment methods and data should evolve, and the wishlist is long. Limiting this wishlist to the scope of this thesis, taking into account both data and methods, four aspects arise:

1. Addressing feedback effects (dynamic models, rebound effects, … of electricity use and final consumption in general);
2. Refining the data, as more local or region-specific models would lead to more accurate results and targeted policymaking, and limit uncertainty (so far not properly captured);

3. Developing "meso-level" models, with THEMIS, and in a relatively rudimentary way, combining technology-specific datasets (typically LCI data) with economic backgrounds (typically IO data) has proved to be a successful way to provide more complete information, yet these two extremes of a same spectrum rarely meet;
4. Traditional LCA or IO models are flawed by design. Whatever the granularity of the data, these models are simplified by assumptions on linearity and allocation. What follows is the inherent ill representativeness of specific case studies and the difficulty to tackle scale.

4.2.1 FEEDBACKS

Integrated hybrid LCA as used in THEMIS accounts for the feedback from foreground to background systems. By closing the loop between upstream use and downstream supply, we can capture the virtuous or vicious cycles that accompany the development of a technology: if an emerging technology makes a market more efficient, then producing that technology using products from that same market will be more efficient, and conversely when introducing a lower-than-average efficiency technology. It is straightforward to conceive in the case of electricity since nearly all processes in most industrial systems use electricity, but this is valid for any other system. Making fuel efficiency regulations of on-road transportation more stringent (say reducing fuel consumption by 10%) will have an effect in lowering emissions from passenger cars of final consumers (by about 10%), but also from road transportation all along the car and fuel value chain. This will not only reduce direct emissions (which would be less than a 10% reduction over the life cycle if the policy is only introduced in the foreground system), but all road transport-related life cycle emissions of passenger transportation by as much as the regulation dictates (10%). These "hardcoded" feedback effects are easy to capture as they appear naturally in the calculations, however THEMIS cannot address the more complex ones, because of the linearity assumptions. For instance, product substitution and rebound effects could not be assessed.

4.2.2 DATA MANAGEMENT, RESOLUTION

First-hand collection of life cycle inventory data is resource-intensive. Building large-scale databases requires the use of many techniques for disaggregation, approximation, or extrapolation, of a set of data points. In the latest version of the widely-used ecoinvent database (Wernet et al. 2016), the modelling choice is left to the user (cut-off, allocation at the point of substitution, and consequential system models). This decision sets an example of data traceability.

Regional resolution has interestingly been improved quite early in life cycle assessment and multiregional input-output, principally when modelling the technosphere: industrial processes in LCA now systematically take into account regional energy mixes and level of technology, while MRIO tables exist at least at the country level and even at subnational level in particular cases (e.g. Japan). Environmental extensions are sometimes adapted to their actual place of emissions via sub-compartment modelling (e.g. high-density population vs. low-density population for air emissions), but the characterisation of these flows still lacks a clear modelling framework. Efforts are however being made to characterise flows at their point of emissions (Mutel et al. 2012; Curran et al. 2011).

Time resolution is as important as regionalisation, mostly because life cycle thinking does not yet account for the timeline of events in the process chains of a system (Tiruta-Barna et al. 2016). Material and energy inputs are considered punctual in time, and emissions and impacts are modelled according to generic fate model, while characterisation is based on arbitrary time horizons. Overall, LCA results may vary widely depending on how time was accounted in a study. An example of such characterisation “double standard” risks in Paper IV is the fact that ionising radiation is characterised over 100 years after emission (in the hierarchist perspective of ReCiPe (ReCiPe 2012)), while emission numbers retained in the LCI of coal mines is the cumulative sum of all flows over the next 60000 years, according to the time frame standard of modelling in ecoinvent 2.2 (Doka 2009). Endpoint indicators too can clearly undergo some refinement. As an example, the DALY indicator developed by the WHO is defined equal to the sum of Years of Life Lost (YLL) and Years Lost due to Disability (YLD). The second term, YLL, introduces an index, the disability weight (DW), that reflects the severity of a disease, from 0 for perfect health, to 1 for death. This index is inevitably subjective and, consequently, so is the number of DALYs associated with the environmental impact categories associated with the human health damage endpoint.

The take-away message from these examples is that data needs to be absolutely traceable, every piece of information on any data flow known by the practitioner should become metadata. For life cycle inventories and input-output databases, aggregation models should take it from here and provide databases depending on the LCA practitioner's choice and objectives. For life cycle impact assessment methods, more refinement is of course always possible (e.g. differentiating spatially categories like water stress, land use, or DALY endpoint factors), but it should always be up to the practitioner to choose the resolution appropriate to the goal and scope of her study.

4.2.3 MESO-LEVEL MODELS, DATA AVAILABILITY

Throughout the process of building THEMIS, the need for coherent data sources has been increasingly evident. Many ad hoc techniques had to be developed for data reconciliation: correspondence matrices, approximations, or experts' best estimates. THEMIS itself is very much an ad hoc model in the way it was developed. The push for a streamlined database ontology across all kinds of data that practitioners manipulate is essential to unlock the future capabilities of industrial ecology as a field (Pauliuk et al. 2015b). Linkages between MFA, IO, and LCA are becoming ever more necessary as integrated models develop: models themselves should at least obey to a standard format, at most have their inputs and outputs directly machine-readable. A recent article in the Journal of Industrial Ecology calls for the systematic publication of (open source) models and data along articles (Pauliuk et al. 2015a): the benefits of such good practice guidelines would be invaluable to THEMIS, or future versions thereof, via the use, in the long term, of standard ontologies and machine-readable data. It starts with simple practice such as systematically publishing data along with a manuscript. I look forward to practicing life cycle assessment in a shared manner, where data and methods are openly accessible, and where practitioners take the time to exchange.

4.2.4 THE LIMITS OF INDUSTRIAL ECOLOGY MODELS

Our demand-driven models do not always account for the fact that "consumer behaviour is not fully reducible to individuals making rational conscious decisions all the time" (Schot et al. 2016). Extending the models to integrate agent-based modelling could be a first step towards the consideration of (irrational, realistic) consumer behaviour, and sound policymaking (Farmer and Foley 2009). In the present case, although the public do not choose *per se* the energy systems providing their electricity, the social dimension is nevertheless blatantly absent of the whole analysis. It becomes critical when analysing demand and energy efficiency. Efforts to account for consumer choice, from short-term to long-term, generational paradigm shifts, … are made at a limited scale (Stern et al. 2016). It must however remain clear that this is not the role of life cycle assessment, the linearity assumption, discussed in section 1, prevents life cycle methods from capturing behaviours. Still, economy of scale or critical mass effects are almost inexistent in industrial ecology and should be addressed, not by LCA itself, but by other methods to be coupled with LCA. In a time when LCA becomes prominent for various purposes, such as eco-design, policy support, communication, and marketing, it is important to stress that this method only translates a given functional unit into a quantified set of potential environmental and health impacts. As such, it does not provide any elements to qualify the legitimacy and utility of that functional unit, be it the consumption of luxury or necessity products, or the production of weapons or healthcare products.

Not only do process-based LCA and (perhaps to a lesser extent) input-output analysis fail to capture economic mechanisms, but these methods are also unable to capture environmental mechanisms properly, because of their inherent mathematical principles. As noted by Heijungs: "The state of the economy and the environment are outside [the process-picture of the world's] realm. This type of analysis is therefore unable to say anything about stocks in the economy, about background concentrations of chemicals, etc.” (Heijungs 1997). This is not to say that LCA and IO’s basic principles should be revised, but that they limit applications and purposes, and it is undeniable that coupling these methods with other techniques addressing their shortcomings (the same way LCA and IO complete each other in hybrid analysis) will become common practice. Opening up current methods to the coupling with micro- and macroeconomics, chemistry, climate, or social science techniques through integrated assessment models is pivotal to ensuring the relevance of industrial ecology.

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6 APPENDIX

PAPER I

Thomas Gibon, Richard Wood, Anders Arvesen, Joseph D. Bergesen, Sangwon Suh, and Edgar G. Hertwich. 2015. A Methodology for Integrated, Multiregional Life Cycle Assessment Scenarios under Large-Scale Technological Change. *Environmental Science & Technology* 49(18): 11218–11226 (9 pages).

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A Methodology for Integrated, Multiregional Life Cycle Assessment Scenarios under Large-Scale Technological Change

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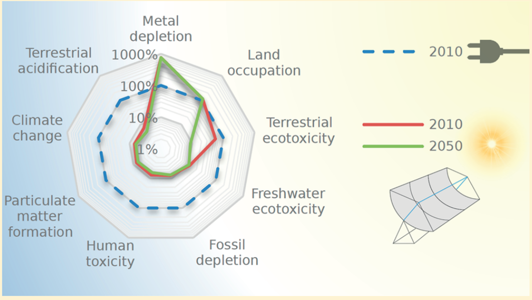
Supporting Information

ABSTRACT: Climate change mitigation demands large-scale technological change on a global level and, if successfully implemented, will significantly affect how products and services are produced and consumed. In order to anticipate the life cycle environmental impacts of products under climate mitigation scenarios, we present the modeling framework of an integrated hybrid life cycle assessment model covering nine world regions. Life cycle assessment databases and multiregional input–output tables are adapted using forecasted changes in technology and resources up to 2050 under a 2 °C scenario. We call the result of this modeling "technology hybridized environmental-economic model with integrated scenarios" (THEMIS). As a case study, we apply THEMIS in an integrated environmental assessment of concentrating solar power. Life-cycle greenhouse gas emissions for this plant range from 33 to 95 g CO_2 eq./kWh across different world regions in 2010, falling to 30–87 g CO_2 eq./kWh in 2050. Using regional life cycle data yields insightful results. More generally, these results also highlight the need for systematic life cycle frameworks that capture the actual consequences and feedback effects of large-scale policies in the long term.



1. INTRODUCTION

A 2 °C global average temperature increase is considered the threshold above which global warming consequences on human health, ecosystems, and resources might be disastrous. Pathways incorporating a combination of a shift toward low-carbon energy technologies, efficiency improvements, and a decrease in final consumption present various ways to reduce greenhouse gas emissions as means to reach climate targets. In effect, climate change mitigation demands large-scale technology change on a global level and, if successful, will significantly affect how products and services are produced and consumed. Understanding the future life cycle implications of this substantial change requires a modeling of technological deployments in the global economy.

In general, life cycle assessment (LCA) studies provide static snapshots of systems at a given moment in the past or in a hypothetical future for a given region. In contrast, energy scenario models trace fuel chains, and do not account for the life cycle aspects related to the energy systems' infrastructure. This paper demonstrates a methodology that combines these approaches to overcome the shortcomings of each. Depending on the large scale impact of a certain technology's deployment, the whole life cycle impact of any given product may be affected. Modifications predicted in climate change mitigation roadmaps address all sectors of the economy, from electricity generation through transportation to cement production. It is therefore essential to assess these modifications based on a model that contains all life cycle phases of both existing and emerging technologies.

Extending LCA to future scenarios is an arguably effective way to understand the implications of long-term changes such as those planned in climate change mitigation roadmaps. In a review of LCA methodology, Guinée et al.[1] argue: "It may be more realistic [than microscopic consequential product LCAs] to start thinking how more realistic, macroscopic scenarios for land use, water, resources and materials, and energy (top-down) (...) can be transposed to microscopic LCA scenarios." In a review of LCAs of energy technology systems, Masanet et al. emphasize the usefulness of combining LCA with input–output analysis and scenario models.[2] A survey by Reap et al.[3] and a more complete summary of the state of the art in LCA by Finnveden et al.[4] raise concerns that the time dimension in LCA is often overlooked. Attempts to address time dependency and scenarios in LCA have increased over the past decade,[5−9] including with the use of input–output analysis.[10−12] In

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scenario modeling, the relevance of including information from LCA is increasingly recognized. The IPCC writes, "By extending scenario analyses to include life cycle emissions and the energy requirements to construct, operate and decommission the different technologies explicitly, integrated models could provide useful information about the future mix of energy systems together with its associated life cycle emissions and the total environmental burden." (see ref 13, p. 729).

Proposed here is a method for assessing the environmental and resource implications of the large-scale adoption of climate change mitigation measures, which includes various scenarios, and present a model implementing this method. We call this model the technology hybridized environmental-economic model with integrated scenarios (THEMIS). We use THEMIS to evaluate technologies from a life cycle perspective by calculating the material and energy inputs and outputs to production, operation and maintenance, and disposal. With the increasing utilization of renewable energy technologies and energy conservation, the importance of quantifying life cycle impacts increases, as relatively fewer impacts take place directly at power stations and relatively more impacts occur upstream in supply chains. The THEMIS framework consists of three main features. (i) A multiregional life cycle assessment framework that hybridizes process LCA and input−output, thereby providing for more complete life cycle inventories, including, for example, the input of services. (ii) The electricity generation and other key activities described in the input−output and life cycle databases reflect the market mixes and production volumes of existing scenario models, including the deployment of novel technologies in specific regions. (iii) The products modeled in the foreground are used in the process LCA and MRIO backgrounds, replacing the production of commodities (e.g., electricity, materials) to the degree foreseen in the scenario. Downstream impacts are thus addressed via linkages between foreground inventories to background processes and sectors. We illustrate this approach in the present paper by applying the resulting model on the life cycle inventory of a concentrating solar power (CSP) plant. Furthermore, THEMIS underpins the results of Hertwich et al., a companion paper that applies its principles to the case of global low-carbon electricity scenarios (including the CSP inventory described here).[14] Other applications have been carried out, taking advantage of the flexibility of the model, using various foreground systems such as lighting[15] or building energy management systems,[16] or even using CEDA (comprehensive environmental data archive[17]) in lieu of EXIOBASE (database originally created for EXIOPOL, externality data and input−output tools for policy analysis[18]) as an input−output background.[19] The present paper focuses on the generic and adaptable framework fundamental to these studies.

2. MATERIALS AND METHODS

2.1. General Outline. In this paper, we present an approach for scenario modeling in LCA as suggested by Guinée et al.[1] We embed a process LCA database in a multiregional input−output (MRIO) description of the global economy[18] using a hybrid LCA framework.[20−23] An LCA database contains physical information regarding the material and energy flows occurring over the life cycle phases of given processes, as well as their associated environmental emissions and natural resource use ("stressors"). An MRIO table is generally defined as a symmetric input−output table containing the domestic monetary transactions of a set of regions, as well as the trade data between these regions. The MRIO database used in this study is extended with environmental stressor data for each economic sector. The frequently cited advantage of hybrid LCA is a more comprehensive coverage of inputs from the use of input−output tables while retaining the detailed process descriptions from process LCA. The current work also provides an additional advantage by embedding process LCA in an MRIO model, giving us the opportunity to capture the structure of regional electricity production under different energy policy scenarios, as illustrated in Lenzen and Wachsmann's study on the geographical variability of the life cycle impacts from wind turbines.[24] Market shares, energy conversion efficiencies and capacity factors are also adjusted to follow regional variations. Furthermore, we link the functional units of the foreground life cycle inventories back into the input−output description of the economy, thus achieving the closure that has been suggested for integrated hybrid LCA.[25] In this way, we also capture the downstream use of the product system by other parts of the economy and its feedback to the economy itself.[26] To note, in this work, we assume a symmetric LCI database; in comparison, Suh provides a general framework for both symmetric and nonsymmetric (but invertible) databases.[25]

In LCA, a distinction is often made between a foreground system, which describes the assessed product system and contains the data collected for most direct inputs, and a background system, which is commonly a generic life cycle inventory (LCI) database.[15,20] In a hybrid LCA, the foreground system typically requires both physical inputs from the process LCI database and economic inputs from the input−output database. We adopt the following notation[22] to describe the technology matrix and its associated variables:

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

$$F_t = (F_{f,t} \quad F_{p,t} \quad F_{n,t}) \tag{2}$$

Here, A and F are the technology and stressor (or factor) matrices, respectively. The index f denotes the set of foreground processes, or the direct inputs to the technology being studied, p indicates the set of physical background processes, and n the set of sectors of the economic input−output system. For example, $A_{fp,t}$ denotes the matrix of coefficients from foreground f to physical background processes p in year t. $A_{ff,t}$, $A_{pp,t}$, and $A_{nn,t}$ are therefore square and symmetrical. $A_{pp,t}$ and $A_{nn,t}$ may be multiregional, and all subsequent equations apply both to single-region or multiregional matrices, unless otherwise mentioned. Since there is no linkage between physical and economic databases ($A_{pp,t}$ and $A_{nn,t}$, respectively), $A_{np,t} = A'_{pn,t} = 0$, an appropriately sized null matrix. Prospective LCA scenario modeling is achieved by integrating the foreground into the background, bringing forth nonzero values in $A_{fp,t}$ and $A_{fn,t}$. When nonzero values are introduced in $A_{fp,t}$ and $A_{fn,t}$, adjustments to the background matrices are needed to avoid double-counting: the background inputs and emissions to the corresponding sector or process are zeroed out, as shown later in eqs 8 and 9. In the following, $\tilde{A}$ denotes a version of a technology matrix that has undergone

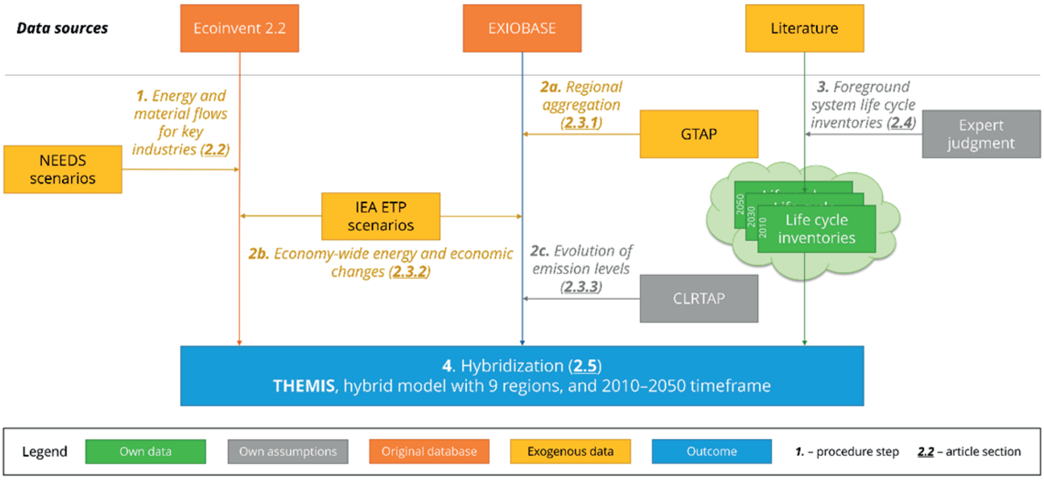

Figure 1. Structure of the model, and interactions between the various data sources. Main data sources are the International Energy Agency's (IEA's) Energy Technology Policy (ETP) scenarios, the *ecoinvent* life cycle inventory database, the *EXIOBASE* multiregional input–output database, and the New Energy Externalities Development for Sustainability (NEEDS) scenarios for life cycle inventories, the Global Trade Analysis Project (GTAP), and the European Convention on Long-Range Transboundary Air Pollution (CLRTAP).

such adjustments. Index t denotes time as matrices are derived for years 2010, 2030, and 2050.

When assessing new energy technologies that are penetrating a market, feedback effects arise. In the case of electricity generation, foreground systems that describe the production of power plants and fuels must become part of the background electricity, which in turn is part of the energy mix used to build future power plants. In the following, *technology* refers to a distinctive category of electricity generating systems using a specific pathway from an energy source to electricity generation (e.g., photovoltaic (PV) technology). A *system* refers to a technology variant (e.g., ground-mounted cadmium-telluride PV system).

The design of THEMIS consists of four steps, shown in Figure 1, and which are described in the next sections. First, we implement technological efficiency improvements of key sectors, such as metals and construction material production and transportation, in the databases in a manner consistent with the scenario. As efficiencies are likely to improve over time, we produce separate tables for each time step (2010, 2030, 2050) that reflect each of the model years according to the nine model regions. Second, we incorporate parameters from the energy scenario in the background LCI and MRIO databases, and adjust the background databases to represent production and consumption in the model years. We also implement separate scenario information for the potential reduction of conventional emissions in the MRIO database following the European Convention on the Long-Range Transboundary Air Pollution (CLRTAP).[27] Third, we compile life cycle inventories for the foreground processes. We model electricity generation specifically, as a change in electricity generation technology will be most radical under climate change mitigation and will have the largest impacts on the life cycle of other products. Inputs to the foreground system can be either physical inputs from the process LCI database or economic inputs from the input–output database. Fourth, we link the foreground life cycle inventories back to the background by replacing technologies already represented in the background, or appending new ones and changing the production mixes of the background with each time step. The model thus becomes fully integrated. The exogenous scenarios altering the original databases are applied in a complementary manner. The NEEDS inventories mainly address industrial processes, whereas the IEA scenarios describe electricity sectors. They are therefore not consistent with each other in a strict sense; however they align with the same target (i.e., a 2 °C global warming by 2050).

The hybrid LCA setup is similar to earlier scenario work for CO_2 capture and storage[28] and wind power.[29] A commonly used process-level LCI database, *ecoinvent* 2.2,[30] serves as $A_{\mathrm{pp},0}$ while a multiregional input–output database, *EXIOBASE*, in its first version,[18] serves as $A_{\mathrm{nn},0}$ in eq 1. Their respective environmental extensions, once harmonized, serve as $F_{\mathrm{p},0}$ and $F_{\mathrm{n},0}$ in eq 2. The BLUE Map and Baseline scenarios of the International Energy Agency's (IEA) Energy Technology Perspectives (ETP)[31] are used to explore two different futures: one with aggressive climate change mitigation, or the BLUE Map scenario, and one without coordinated efforts to reduce greenhouse gas emissions, or the Baseline scenario.

2.2. Adjustments to Process LCI Database.

Ecoinvent 2.2[30] is used as the background process LCI database. The use of a preallocated database is a prerequisite for the following adjustments, which are only valid for a square matrix. In this matrix, electricity mixes are adjusted to align with the respective energy scenarios. These adjusted mixes are presented in the Supporting Information (SI). Likewise, key industrial production processes are altered to represent the projected average technology of 2030 and 2050. These processes are namely aluminum, copper, nickel, iron, and steel, metallurgical grade silicon, flat glass, zinc, and clinker. These processes and their forecasted values are also available in the SI.

We create versions of the *ecoinvent* 2.2 database for each region and time period by changing the electricity mix using matrix multiplication. Let J be an identity matrix of the same size as the *ecoinvent* database's original matrix, A_{orig}. Let k be the index of any power generation technology contributing to the original electricity mix, and l the index of any technology contributing to the new electricity mix. Now let $j_{kk} = 0$ (instead of 1, those being the diagonal elements of J) and $j_{lk} = 1$ (instead of 0). The new database is obtained multiplying the pseudoidentity matrix J with A_{orig}: $A_{new} = JA_{orig}$. This method can be generalized in order to adjust process LCI databases to any set of scenario assumptions.

Life cycle inventories of key industrial processes for 2030 and 2050 are adapted according to the inventories produced by the New Energy Externalities Development for Sustainability (NEEDS) project.[32] The authors of NEEDS developed LCI data fitting to the *ecoinvent* database, using expert judgment and technology roadmaps for various technologies as well as a set of scenarios until 2050 to reflect both assumptions of varying optimism and different policies. We identified NEEDS' realistic-optimistic scenario as the closest match to the BLUE Map scenario assumptions, namely the deployment of best available techniques, and reasonable efficiency trends. We applied these exogenous data in a complementary way.

2.3. Adjustments to Input−Output Database. A nine-region MRIO model is constructed to reflect the nine world regions represented by IEA energy scenarios.[31] These regions are formed by aggregating the countries and regions from the *EXIOBASE* database.[18] To be consistent with the process-based life cycle inventory database, the symmetric commodity-by-commodity input−output tables of *EXIOBASE* are selected for use in the model. Since there is no perfect many-to-one match between the original 44 *EXIOBASE* regions and nine IEA regions, the higher-resolution GTAP MRIO model[33] is used to split the large "rest of world" IEA region, as shown in the SI. Forecasted electricity generation and installed capacity data provided by the IEA are also used to adapt the database to current and future years. Several important parameters implemented in THEMIS are include population; GDP; industry final energy demand; total primary energy demand and final energy consumption (including nonenergy use) of coal, oil, gas, heat, biomass, and waste and other renewables; power generation capacity and actual annual power production for 15 types of electricity generation sectors (section 1 of the SI); investment sums; operation and maintenance costs; efficiency; and learning rate for these technologies. Other parameters and data needed for disaggregation or to adjust parameters in the original data are presented in Sections 4−9 in the SI. Regional aggregation is achieved simultaneously with the disaggregation of electricity sectors, as presented in the next section.

Electricity supply is modeled in the original version of *EXIOBASE* through six electricity sectors: coal, natural gas, nuclear, hydropower, wind power, and a category for all remaining electricity sources, "oil, biomass, waste and nowhere else classified". The total number of sectors is m (here, m = 129). We expand this set of electricity supply sectors with eight additional technologies: coal with carbon dioxide capture and storage (CCS), natural gas with CCS, biomass and waste, biomass and waste with CCS, ocean and tidal, geothermal, solar photovoltaics, and concentrating solar power. We further disaggregate the wind power sector into the wind onshore and wind offshore sectors, therefore adding nine electricity sectors. New electricity mixes are applied to the existing database through the modification and disaggregation of electricity sectors in the coefficient matrix. The original number of electricity sectors is k (here $k = 6$), while the new number of sectors is l ($l = 15$). See section 6 of the SI for the redistribution of inputs to each electricity sector. The new electricity share vectors, v_c, contain $m - k + l$ elements for a given country or region, c. The sum of any row of v_c equals one. The conversion matrix H_{el} has as many columns as the original coefficient matrix (A_{nn}) and as many rows as the new one (defined as $\tilde{A}_{nn}$). The blocks of H_{el} that correspond to domestic electricity-to-electricity flows (of dimensions $k \times l$) are populated with the elements of $v_c i$, with i being a row vector of m ones.

In the case of a multiregional matrix, regional aggregation can be achieved simultaneously with electricity sector disaggregation. In this case, a region-to-region concordance matrix, H_{reg}, of dimensions $r_{orig} \times r_{new}$, with r_{orig} the original number of regions (before aggregation; here, 44) and r_{new} the new number of regions (after aggregation; here, nine) is required. A new concordance matrix $H_{reg,el}$ can then be computed from H_{reg} and H_{el} as follows: $H_{reg,el} = H_{reg} \otimes H_{el}$, where $\otimes$ denotes the matrix direct product, or Kronecker product.[34] $H_{reg,el}$ has dimensions $r_{orig}k \times r_{new}l$. eq 3 describes the simultaneous process of electricity sector disaggregation and regional aggregation for a multiregional matrix.

$$\tilde{A}_{nn} = H_{reg,el} A_{nn} H'_{reg,el} \tag{3}$$

Market shares of new electricity systems are estimated based on a combination of IEA scenario data for the technology market shares, and expert judgment for the system market shares. Detailed market shares can be found in the SI. The input of each foreground system to the background electricity mix, h_{ij}, is therefore a multiplication of two (or three) factors:

$$h_{fp,ij} = \alpha_i \beta_{ij} \tag{4}$$

$$h_{fn,ij} = \alpha_i \beta_{ij} \gamma_{ij} \tag{5}$$

The values $h_{fp,ij}$ and $h_{fn,ij}$ are the flows of the foreground-to-background quadrant of the technology matrix for the process-LCA and the input−output parts, respectively. Inventories are constructed and scaled to a functional unit, the mathematical quantity of product delivered by a system, typically one plant or one kWh. Additional factors are introduced to scale this flow appropriately. In eqs 4 and 5, α_i is the inventory scaling factor, in kWh per functional unit, that is, "one plant" or "one kWh" in a specific region, at row i. The value β_{ij} is the share of functional unit i in process or product j, that is, the physical share of each electricity generating system's functional unit entering a corresponding background's electricity process. Finally, in eq 5 only, where a conversion to monetary unit is required, γ_{ij} is the price of one scaled functional unit, in euro per kWh in the present case. Prices are derived from an IEA report on the levelized costs of electricity (LCOE) and presented in the SI.[35]

Atmospheric emissions intensities per sector are also likely to change due to improved efficiency and pollution control policy. The atmospheric emissions considered in *EXIOBASE* include greenhouse gases, heavy metals and particulate matter. These substances are controlled, reported, and regulated. To estimate the future evolution of national emissions, we have assumed continuity with the historical evolution of most of these pollutants in Europe. The model thus relies on the assumption that future emissions per euro will decrease as pollution control technologies improve and regulations become stricter worldwide, and that it will do so at the same pace as it has in Europe for two decades. To project these potential changes in the model, we adapt existing trends of certain pollutants from 1990 to 2009 in the EU27 from the Convention on Long-Range Transboundary Air Pollution (CLRTAP) historical data for the

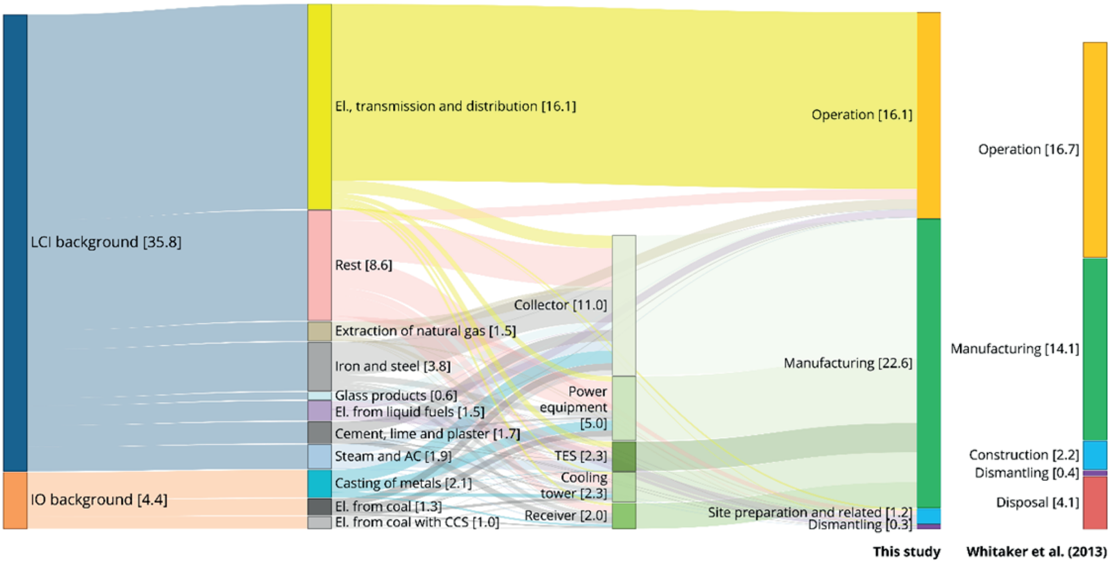

Figure 2. Contribution analysis of the impact on climate change of hybrid LCA results for 1 MWh of electricity produced by a concentrating solar power plant, central tower, in the North America region, in kg CO_2 eq Right hand side: foreground contribution analysis in this study vs Whitaker et al.[37] TES = thermal energy storage, El. = electricity.

EU27 for the following pollutants: Cd, CO, dioxins, HCB, HCH, mercury, NH_3, NMVOC, NO_x, lead, PCB, PM_{10}, $PM_{2.5}$, SO_x, and total PAH.[27] With the notable exception of copper emissions and arsenic emissions, these pollutants cover the most important environmental stressors used in *EXIOBASE* that contribute to the selected impact categories. We take the following approach to adapt these data to our model: pollutant emissions are normalized by the total GDP of the EU27 countries during the time period of 1990–2009 in order to adjust for changes in economic output that could increase or decrease overall emissions. For each substance, a linear ordinary least-squares regression is used to model the trend in emission levels in the 1990–2009 time period and, on this basis, extrapolated to 2050. Finally, improvement factors are derived from this extrapolation. This method is a first approximation of what can be achieved under continued efforts in pollutant control. Regressions are shown in the SI. Best estimates are used to reallocate inputs after disaggregation; Section 6 of the SI shows how economic sectors were linked to each electricity sector.

2.4. Foreground System LCI. Emerging and future technologies such as coal- and gas-fired power plants with carbon capture and storage, large onshore wind turbines, or concentrating solar power plants are underrepresented in *ecoinvent* 2.2; we have therefore built life cycle inventories for missing or misrepresented processes. Data sources for these life cycle inventories are listed in the SI. A key feature of this modeling framework is the use of foreground systems; in this implementation, we use the inventories compiled in Hertwich et al.[14]

2.5. Hybrid Integration. Upstream requirements include all flows from background sectors to the foreground life cycle inventories. All flows from either process or economic background to foreground are provided for each technology. Both process-to-economic (A_{pn}) and economic-to-process (A_{np}) backgrounds are represented by zero matrices. In other words, economic sectors are assumed to give a complete representation of the economy, and process life cycle inventories are not hybridized. Double-counting is assumed to be avoided at the data collection stage.

Downstream flows comprise all flows from the foreground systems to any background sector. In our case, downstream flows stem from the modeled electricity generation systems in the foreground to the appropriate electricity generation mixes or sectors in the backgrounds. Their inclusion can be regarded as the key operation that completes the integration.

$$A_{fp} = H_{fp} \quad (6)$$

$$A_{fn} = H_{fn} \quad (7)$$

where H_{fp} and H_{fn} are matrices containing $h_{fp,ij}$ and $h_{fn,ij}$, respectively, from foreground process to life cycle inventory database and input–output database. These two matrices are structurally sparse, with only a few elements linking the foreground and background.[35]

Adjustments are required in the process-to-process background technology matrix:

$$\tilde{A}_{nn} = A_{nn}\widehat{\overline{i'H_{fn}}} \quad (8)$$

where i is an appropriately sized vector of ones, ′ denotes transposition, ¯ denotes the logical complementary operator (that changes nonzero values into zeros and vice versa), and ^ denotes diagonalization. eq 8 zeroes out the sectors of A_{nn} that are already addressed by a market mix of foreground systems. It is equivalent to assuming that hybrid foreground systems are considered representative of an entire sector.

The same operation is applied to the stressor matrix, in which we assume that all direct emissions and direct requirements to and from the environmental compartments are covered by the foreground systems.

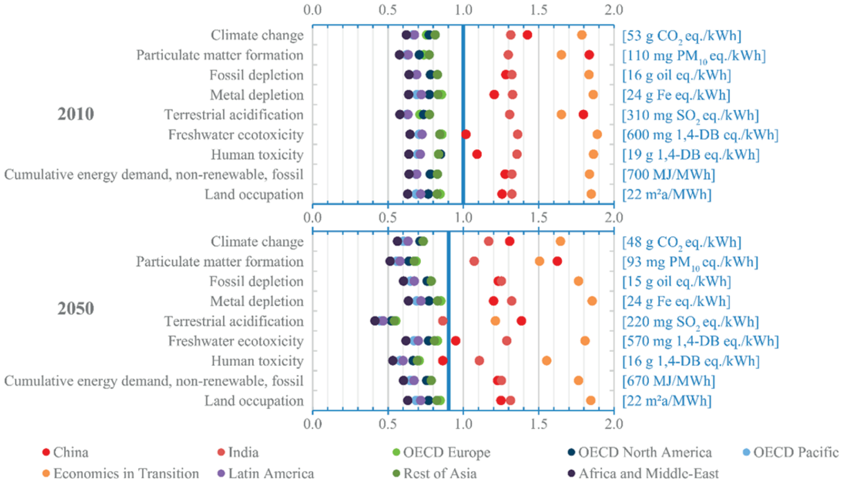

Figure 3. Comparison of selected life cycle impact assessment results of a concentrating solar power plant installed in each of the nine world regions for 2010 and 2050. The world average in 2010, weighted by regional expected production in 2050, is set to 1, with the absolute values on the right-hand side, in blue.

$$\tilde{F}_n = F_n \widehat{i' H_{fn}} \tag{9}$$

2.6. Impact Assessment. Once adapted, the model yields impact assessment results following eqs 10a and 10b.

$$d_t = CF_t (I - A_t)^{-1} y_t = CF_t x_t \tag{10a}$$

$$d_t = C\begin{pmatrix} F_{f,t} & F_{p,t} & F_{n,t} \end{pmatrix} \left(I - \begin{pmatrix} A_{ff,t} & A_{fp,t} & A_{fn,t} \\ A_{pf,t} & A_{pp,t} & A_{pn,t} \\ A_{nf,t} & A_{np,t} & A_{nn,t} \end{pmatrix} \right)^{-1} \begin{pmatrix} y_{f,t} \\ y_{p,t} \\ y_{n,t} \end{pmatrix} \tag{10b}$$

where d_t is the vector of environmental impacts at year t; C is a characterization matrix containing factors from ReCiPe 1.08;[36] F_t is the stressor matrix of the model, designed as described in section 2.3, at year t; A_t is the hybridized technology matrix at year t; and x_t and y_t are the total output and final demand at year t. Contribution analysis can be performed at the consumption level eq 11), production level eq 12, or through the advanced contribution analysis approach (eqs 15 and 16. The diagram shown in Figure 2 uses eq 16.

$$D_{pro,cons} = CF_t (I - A_t)^{-1} \hat{y}_t \tag{11}$$

$$D_{pro,prod} = CF_t \widehat{(I - A_t)^{-1} y_t} = CF_t \hat{x}_t \tag{12}$$

$$D_{pro,ff,t} = CF_{f,t} \widehat{(I - A_{ff,t})^{-1} y_{f,t}} = CF_{f,t} \widehat{x_{f,t}} \tag{13}$$

$$D_{pro,bf,t} = C\begin{pmatrix} F_{p,t} & F_{n,t} \end{pmatrix} \left(I - \begin{pmatrix} A_{pp,t} & A_{pn,t} \\ A_{np,t} & A_{nn,t} \end{pmatrix} \right)^{-1} \begin{pmatrix} A_{pf,t} \\ A_{nf,t} \end{pmatrix} \widehat{x_{f,t}} \tag{14}$$

$$D_{pro,f,t} = D_{pro,ff,t} + D_{pro,bf,t} \tag{15a}$$

$$= C\begin{pmatrix} F_{f,t} & F_{p,t} & F_{n,t} \end{pmatrix} \begin{pmatrix} \widehat{x_{f,t}} \\ \left(I - \begin{pmatrix} A_{pp,t} & A_{pn,t} \\ A_{np,t} & A_{nn,t} \end{pmatrix} \right)^{-1} \begin{pmatrix} A_{pf,t} \\ A_{nf,t} \end{pmatrix} \widehat{x_{f,t}} \end{pmatrix} \tag{15b}$$

$$= CF_t \begin{pmatrix} I \\ (I - A_{bb,t})^{-1} \begin{pmatrix} A_{pf,t} \\ A_{nf,t} \end{pmatrix} \end{pmatrix} \widehat{x_{f,t}} \tag{15c}$$

$$D_{pro,GWP,f,t} = \widehat{C_{GWP} F_t} \begin{pmatrix} I \\ (I - A_{bb,t})^{-1} A_{bf,t} \end{pmatrix} \widehat{x_{f,t}} \tag{16}$$

3. CASE STUDY

We illustrate the THEMIS model by calculating the life cycle environmental impacts of a concentrated solar power (CSP) plant based on foreground inventory data from Whitaker et al.[37] This inventory is developed in Hertwich et al.,[14] but we use it here to demonstrate the use of the method across the integrated framework. Whitaker et al. state that the original inventory was compiled in a hybrid "top-down" perspective, in which the input—output database was used when "the materials inventory for a specific component was not available," and when they "deemed that the environmental impacts resulting from a product's manufacture could not be accurately evaluated by summing the cumulative impacts of constituent raw materials."[37] The original power tower CSP plant is a 106 MW facility situated in Arizona, equipped with a two-tank thermal energy storage system. We adapted the original inventory to the THEMIS framework and performed an analysis simultaneously for the nine world regions. We performed a contribution analysis and compared the outcome with the original results.

Figure 2 shows the contribution of different processes and economic sectors, components, as well as life cycle stages, to the total greenhouse gas emissions. The life cycle stages are compared to those in the original study,[37] in which the life cycle greenhouse gas emissions of the central tower power plant amount to 37 g CO_2 eq per kWh. The results obtained with THEMIS span from 33 to 95 g CO_2 eq per kWh, for plants built and operated in the Africa and Middle-East region and the Economies in transition regions respectively, in 2010. This range falls to 30−87 in 2050. The main contributions to the life cycle greenhouse gas emissions are from the direct use of electricity from the grid (for auxiliary heating[37]), and iron and steel manufacturing, both from the LCI and the IO backgrounds. The Africa and Middle-East region offers the best direct normal insolation (DNI), 2468 kWh/m^2/year, whereas the Economies in transition region offers a lower insolation of 1991 kWh/m^2/year, as derived from Trieb et al.[38] The DNI assumed in the original LCI is 2400 kWh/m^2/year.[37] The climate change impact of a similar power tower plant therefore varies regionally, namely due to the variability of these aspects across regions: background industrial efficiencies, electricity mixes (especially as the operation and maintenance phase requires a substantial quantity of electricity), and DNI.

The assessment can be extended to other environmental impacts, as illustrated in Figure 3, representing the environmental impacts of 1 kWh of electricity produced at plant, for a set of ten indicators. Figure 3 displays a significant regional variation of impact indicator results, which are due to the regional differences in manufacturing. These regional differences are in turn caused by the differences in background industrial processes and in plant operation parameters resulting from differences in climate and achievable capacity factors. More specifically, the results for land occupation reflect differences in the DNI, while the other indicators reflect differences in both the DNI and in the regional technologies used to manufacture and operate the power plants. We can see, for example, that Latin America has below-average pollution-related environmental indicators, reflecting the larger share of hydropower in its energy mix. The Economies in Transition region has particularly high fossil fuel depletion and greenhouse gas emissions, reflecting both the low efficiency of the employed technologies and the intensive use of coal power. Similarly, China has high pollution-related indicators reflecting both the use of coal and the limited use of pollution control processes. It is worth mentioning that the Chinese coal sector has recently undertaken considerable improvements at the technological and provincial levels that have not been captured here. Henriksson et al. have indeed shown that greenhouse gas emission improvements are 2.5 times higher than *ecoinvent* 2.2's coal-based electricity production process for China.[39]

4. DISCUSSION

4.1. Implications. The application of THEMIS reveals that temporal and regional variations can have a significant impact on life cycle inventory results. In its current implementation, THEMIS focuses on the temporal and regional variation of electricity and key materials, which are responsible for a significant share of overall environmental problems. In the future, more parameters can be incorporated and adjusted by using the approach demonstrated in this paper. Consequently, the range of results yielded for a single technology may increase, and the dependence of impacts on these additional factors can be explored in a comparative analysis.

A core advantage with THEMIS is that it represents an integrated hybrid LCA of technologies, with the explicit inclusion of regional penetration rates. Traditionally, researchers have seen the reduction of cutoff errors as the main advantage of hybrid LCA, as the input−output table can trace thousands of process chains that are individually small but cumulatively important. The contribution from input−output sectors in Figure 2 shows that this advantage is also realized for concentrating solar power in the present model. The most important feature of THEMIS, however, is that the results of the foreground are fed back to the background system, contrary to most published hybrid LCAs. Thus, THEMIS is an integrated hybrid analysis where electricity from CSP becomes part of the electricity mix used to manufacture new CSP components. In this way, the analysis not only traces the upstream impacts of CSP production but also the effects of CSP use, an aspect seen as important for the prospective assessment of the impact of technologies.[26,40]

We show that the multiregionality of THEMIS is a clear advantage in comparing the implementation of similar systems across various world regions, climate, and other local characteristics. The analysis of a single system may lead to wide variations from region to region, especially for relatively local environmental impacts such as terrestrial ecotoxicity and acidification.

Life cycle assessment of systems in their future context appears to be essential to understand the various environmental impacts of mature and developing technologies. In the context of electricity generation, this remark is all the more important as electricity is an input to every sector in the economy. In this specific case, we observe previously unquantified feedback effects, now captured in THEMIS.[14] THEMIS has been used for various purposes. Bergesen et al. performed a comparative assessment of thin-film photovoltaic (PV) technologies using THEMIS as well as two hybrid life cycle inventories (foregrounds) representing the current and future design of two thin-film PV technologies, without full integration.[19] Hertwich et al. fully integrated foregrounds to the background data, to include assessed inventories in the various background electricity mixes. Hertwich et al. employed vintage capital modeling such that the construction, operation and decommissioning of each foreground system occur at different time points in the prospective model, thereby capturing technological improvements over the lifetime of energy systems.[14] Furthermore, the THEMIS modeling framework is currently being applied in two upcoming reports from the International Resource Panel to the United Nations Environment Programme regarding the cobenefits and adverse side effects of climate change mitigation technologies.[41] The second of these reports will contribute to a special issue of the *Journal of Industrial Ecology*; in this analysis, the THEMIS model is applied to quantify the prospective future impacts of demand-side energy efficiency technologies such as efficient light sources, efficient copper industrial cogeneration, electric vehicles, building envelope technologies, and demand management.

As energy systems develop both qualitatively through the adoption of new technologies, and quantitatively through efficiency gains and increases in installed capacity, their life cycle environmental impacts will change. For long-term decision-making based on sustainability, understanding future impacts of low-carbon technologies in addition to current impacts is necessary, as these technologies will represent the upstream energy generation used in future materials production and economic activity. The LCA model can be used for prospective analysis of products. An integrated and prospective model, like ours, is essential to properly understand how the environmental impacts of products may change under scenarios of technological change.

4.2. Limitations and Recommended Further Work. The combination of a heterogeneous set of data sets and their integration to existing databases introduce a number of inherent uncertainties. We have been especially careful to select compatible scenarios (e.g., NEEDS' "realistic-optimistic" and IEA's BLUE Map scenarios) in order to maintain a consistent set of assumptions. In particular, electricity price and cost assumptions, as well as the extrapolations of emissions trends are uncertainties that should be addressed in further research. First, electricity prices are modeling assumptions that link physical inventories with the input−output data, and are therefore part of a technological description of a sector. Quantifying their absolute uncertainty (namely across regions and years) is beyond the scope of this paper, but the price assumptions still allow relative comparison between technologies, regions, and years. Second, applying the emission levels extrapolated from the 1990−2009 European regulation trends for 16 atmospheric pollutants to all regions carries substantial uncertainty. This methodological choice was made based on data availability and on a level of ambition comparable to the NEEDS' and BLUE Map scenarios. As a reference for comparison, note that the emissions level is not adapted in the Baseline scenario.

Investments and capital formation have not been explicitly implemented in the model. Change to the use of capital stock has not been included in the IO part of the model (IO databases generally report annual flows of goods/services, with use of capital stock as an exogenous input). As suggested by Suh, making investments endogenous is a way to tackle that issue.[42] This limitation can be removed with the inclusion of capital consumption in the IO matrix. For present purposes, however, this limitation is a minor one, as inputs from the IO system are not indirectly capital intensive.

Another potential iteration of the THEMIS model would incorporate further integration of energy efficiency technologies into the foreground and background of the model. For example, the changing efficiency and impacts of metals production (e.g., copper) could further influence the long-term impacts of renewable energy technologies, thereby introducing even more feedback effects. Also, the deployment and technological development of electric and hybrid vehicles for both passenger and freight transport would similarly affect the life cycles of many products and services.

While it is impossible to predict which technologies will dominate the electricity market in 2050, it is nevertheless important to integrate all candidates in an existing LCA and input−output database. Additional research is needed to quantify uncertainty in technology adoption (e.g., market shares) and the rate of technological development (e.g., how quickly photovoltaic technologies will reach maturity). Despite these uncertainties, scenario assessment is a key to designing sustainable futures, and the THEMIS model is capable of performing due-diligence studies of long-term, low-carbon energy development scenarios.

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.est.5b01558.

> Data used to modify the original databases has been gathered in two accompanying files (PDF) (XLSX)

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Notes

The authors declare no competing financial interest.

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PAPER I, SUPPLEMENTARY INFORMATION

The following appendix to Paper I (9 pages) is available online at
http://pubs.acs.org/doi/suppl/10.1021/acs.est.5b01558/suppl_file/es5b01558_si_001.pdf

Additionally, various Excel files used in the model construction process are downloadable from
http://pubs.acs.org/doi/suppl/10.1021/acs.est.5b01558/suppl_file/es5b01558_si_002.xlsx

These Excel files are not included in the thesis.

Supporting Information for:

A methodology for integrated, multiregional life cycle assessment scenarios under large-scale technological change

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- Number of figures: 5

1 Data

Data used to modify the original databases has been gathered in an accompanying Excel file, “Gibon_Supporting_Information.xlsx”. The following sections describe the various datasets. It excludes the life cycle inventories, available in Hertwich et al. (2015)[1].

Electricity mixes used as input in the model are adapted from a dataset we obtained from the International Energy Agency (IEA). Section 1 of the SI contains the values for installed capacity of fifteen electricity production technologies, for the years 2007, 2030 and 2050, nine world regions, and for the two IEA scenarios BLUE Map and Baseline.

Industrial processes described in the “LCA of background processes” report of the NEEDS project have been used to modify the LCI database and the energy inputs of the MRIO database. The optimistic realistic assumptions (reasonable goals, 440-ppm electricity mix scenario) have been considered to match the BLUE Map assumptions, and the pessimistic scenario (no technological development) to match the Baseline assumptions.

Lower heating values for various energy carriers have been used to estimate the energy efficiency improvement of the industrial processes described in section 2 of the SI.

Regional aggregation is described in the Excel file, as a correspondence table between EXIOBASE regions and the IEA’s regions.

IEA region classification is presented.

Electricity sectors after disaggregation are described, as well as the redistribution of IO inputs after the disaggregation process.

Market shares. Estimates of the respective market share of each system within each technology cluster. Electricity mixes are given in section 1 of the SI.

Lifetimes of every system.

Levelized cost of electricity. The cost of electricity production system by system, has been used as an estimate for the amount of each system's functional unit per euro of electricity sector in the IO part of THEMIS.

2 Emissions modelling

All the emissions accounted in EXIOBASE have been modified with the assumption that their global volumes follow exponential decay behavior. Emission inventories for the European Union have been used as proxies for the forecasting of air emissions [2].

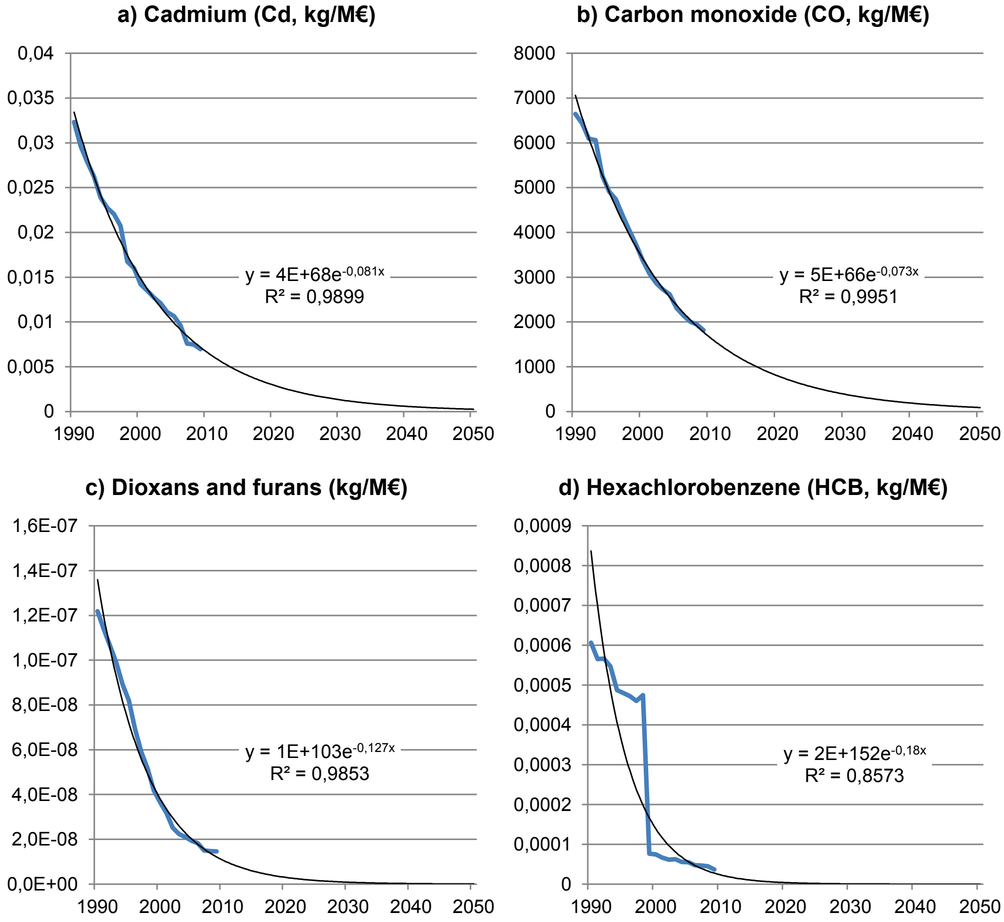


Figure S1. Fitting air emission intensities for the period 1990-2009. Future intensities (2010-2050) were derived from the exponential decay regression, for cadmium (a), carbon monoxide (b), dioxins and furans (c) and hexachlorobenzene (d).

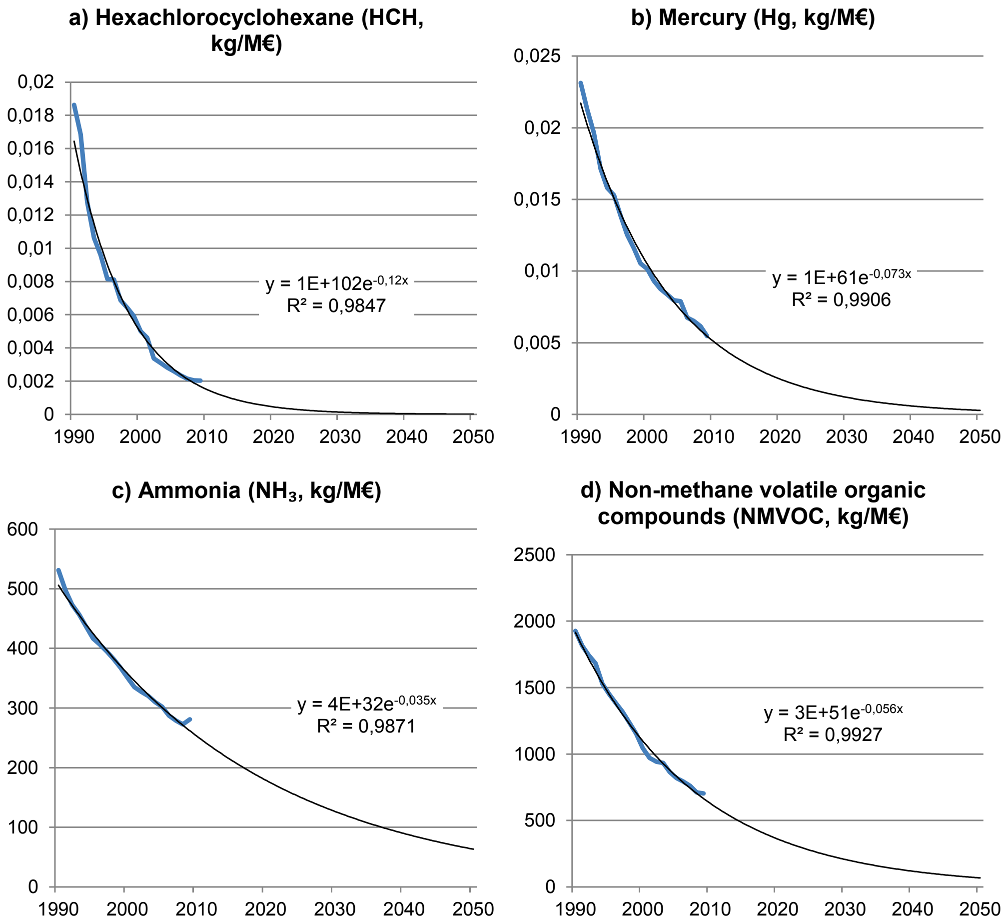
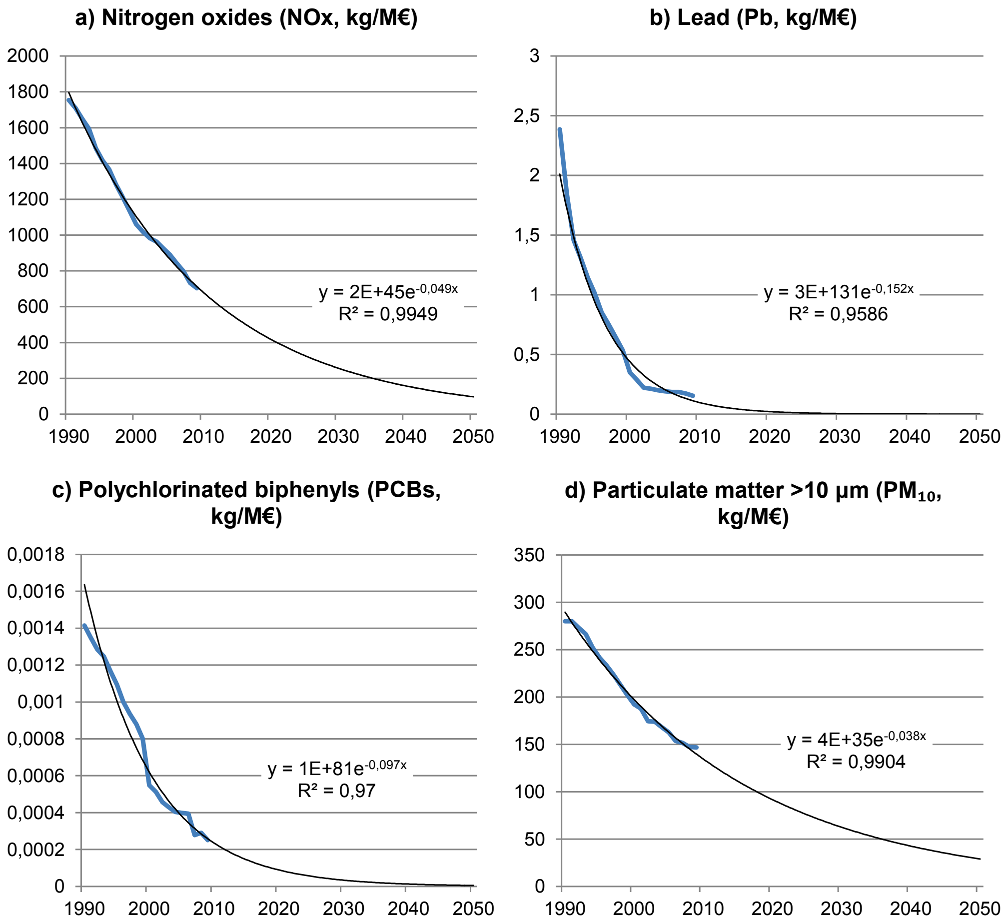


Figure S2. Fitting air emission intensities for the period 1990-2009. Future intensities (2010-2050) were derived from the exponential decay regression, for hexachlorocyclohexane (a), mercury (b), ammonia (c) and NMVOC (d).



a) Nitrogen oxides (NOx, kg/M€)

b) Lead (Pb, kg/M€)

c) Polychlorinated biphenyls (PCBs, kg/M€)

d) Particulate matter >10 µm (PM$_{10}$, kg/M€)

Figure S3. Fitting air emission intensities for the period 1990-2009. Future intensities (2010-2050) were derived from the exponential decay regression, for cadmium (a), carbon monoxide (b), dioxins and furans (c) and hexachlorobenzene (d).

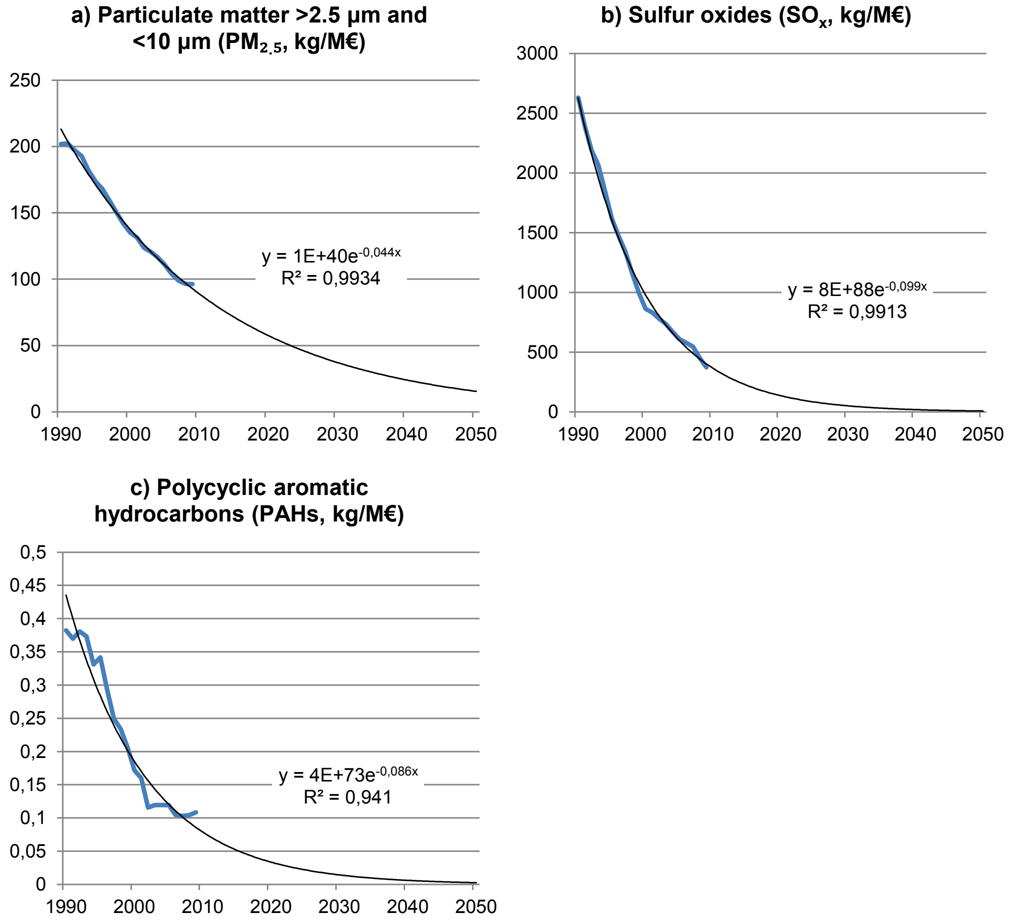


Figure S4. Fitting air emission intensities for the period 1990-2009. Future intensities (2010-2050) were derived from the exponential decay regression, for cadmium (a), carbon monoxide (b), dioxins and furans (c) and hexachlorobenzene (d).

3 Simplified model setup

Figure S5. Simplified THEMIS setup.

4 References

1. Hertwich, E. G.; Gibon, T.; Bouman, E. A.; Arvesen, A.; Suh, S.; Heath, G. A.; Bergesen, J. D.; Ramirez, A.; Vega, M. I.; Shi, L., Integrated life-cycle assessment of electricity-supply scenarios confirms global environmental benefit of low-carbon technologies. *Proc. Natl. Acad. Sci. U. S. A.* **2015,** *112*, (20), 6277-6282.
2. European Environment Agency *European Union emission inventory report 1990–2011 under the UNECE Convention on Long-range Transboundary Air Pollution (LRTAP)*; Luxembourg, 2013.

PAPER II, WITH SUPPLEMENTARY INFORMATION

Edgar G. Hertwich, Thomas Gibon, Evert A. Bouman, Anders Arvesen, Sangwon Suh, Garvin A. Heath, Joseph D. Bergesen, Andrea Ramírez, Mabel I. Vega, and Lei Shi. 2015. Integrated life-cycle assessment of electricity-supply scenarios confirms global environmental benefit of low-carbon technologies. *Proceedings of the National Academy of Sciences of the United States of America* 112(20): 6277-6282 (6 pages + SI: 39 pages).

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

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Edited by William C. Clark, Harvard University, Cambridge, MA, and approved September 3, 2014 (received for review July 31, 2013)

Decarbonization of electricity generation can support climate-change mitigation and presents an opportunity to address pollution resulting from fossil-fuel combustion. Generally, renewable technologies require higher initial investments in infrastructure than fossil-based power systems. To assess the tradeoffs of increased up-front emissions and reduced operational emissions, we present, to our knowledge, the first global, integrated life-cycle assessment (LCA) of long-term, wide-scale implementation of electricity generation from renewable sources (i.e., photovoltaic and solar thermal, wind, and hydropower) and of carbon dioxide capture and storage for fossil power generation. We compare emissions causing particulate matter exposure, freshwater ecotoxicity, freshwater eutrophication, and climate change for the climate-change-mitigation (BLUE Map) and business-as-usual (Baseline) scenarios of the International Energy Agency up to 2050. We use a vintage stock model to conduct an LCA of newly installed capacity year-by-year for each region, thus accounting for changes in the energy mix used to manufacture future power plants. Under the Baseline scenario, emissions of air and water pollutants more than double whereas the low-carbon technologies introduced in the BLUE Map scenario allow a doubling of electricity supply while stabilizing or even reducing pollution. Material requirements per unit generation for low-carbon technologies can be higher than for conventional fossil generation: 11–40 times more copper for photovoltaic systems and 6–14 times more iron for wind power plants. However, only two years of current global copper and one year of iron production will suffice to build a low-carbon energy system capable of supplying the world's electricity needs in 2050.

land use | climate-change mitigation | air pollution | multiregional input–output | CO_2 capture and storage

A shift toward low-carbon electricity sources has been shown to be an essential element of climate-change mitigation strategies (1, 2). Much research has focused on the efficacy of technologies to reduce climate impacts and on the financial costs of these technologies (2–4). Some life-cycle assessments (LCAs) of individual technologies suggest that, per unit generation, low-carbon power plants tend to require more materials than fossil-fueled plants and might thereby lead to the increase of some other environmental impacts (5, 6). However, little is known about the environmental implications of a widespread, global shift to a low-carbon electricity supply infrastructure. Would the material and construction requirements of such an infrastructure be large relative to current production capacities? Would the shift to low-carbon electricity systems increase or decrease other types of pollution? Energy-scenario models normally do not represent the manufacturing or material life cycle of energy technologies and are therefore not capable of answering such questions. LCAs typically address a single technology at a time. Comparative studies often focus on a single issue, such as selected pollutants (7), or the use of land (8) or metals (9, 10). They do not trace the interaction between different technologies. Existing comparative analyses are based on disparate, sometimes outdated literature data (7, 11, 12), which raises issues regarding differences in assumptions, system boundaries, and input data, and therefore the comparability and reliability of the results. Metaanalyses of LCAs address some of these challenges (13, 14), but, to be truly consistent, a comparison of technologies should be conducted within a single analytical structure, using the same background data for common processes shared among technologies, such as component materials and transportation. The benefits of integrating LCA with other modeling approaches, such as input–output analysis, energy-scenario modeling, and material-flow analysis have been suggested in recent reviews (7, 15).

We analyze the environmental impacts and resource requirements of the wide-scale global deployment of different low-carbon electricity generation technologies as foreseen in one prominent climate-change mitigation scenario [the International Energy Agency's (IEA) BLUE Map scenario], and we compare it with the IEA's Baseline scenario (16). To do so, we developed an integrated hybrid LCA model that considers utilization of the selected energy technologies in the global production system and includes several efficiency improvements in the production system assumed in the BLUE Map scenario. This model can

Significance

Life-cycle assessments commonly used to analyze the environmental costs and benefits of climate-mitigation options are usually static in nature and address individual power plants. Our paper presents, to our knowledge, the first life-cycle assessment of the large-scale implementation of climate-mitigation technologies, addressing the feedback of the electricity system onto itself and using scenario-consistent assumptions of technical improvements in key energy and material production technologies.

Author contributions: E.G.H., T.G., and S.S. designed research; E.G.H., T.G., E.A.B., A.A., S.S., G.A.H., J.D.B., A.R., M.I.V., and L.S. performed research; T.G., E.A.B., A.A., and J.D.B. contributed new reagents/analytic tools; E.G.H., T.G., E.A.B., A.A., and J.D.B. analyzed data; and E.G.H., T.G., E.A.B., A.A., S.S., G.A.H., J.D.B., A.R., M.I.V., and L.S. wrote the paper.

The authors declare no conflict of interest.

This article is a PNAS Direct Submission.

Data deposition: The life-cycle inventory data are available on the Norwegian University of Science and Technology website, www.ntnu.no/documents/10370/1021067956/Environmental+assessment+of+clean+electricity.

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This article contains supporting information online at www.pnas.org/lookup/suppl/doi:10.1073/pnas.1312753111/-/DCSupplemental.

address the feedback of the changing electricity mix on the production of the energy technologies.

We collected original life-cycle inventories for concentrating solar power (CSP), photovoltaic power (PV), wind power, hydropower, and gas- and coal-fired power plants with carbon dioxide (CO_2) capture and storage (CCS) according to a common format, and we provide these inventories in *SI Appendix*. Bioenergy was excluded because an assessment would require a comprehensive assessment of the food system, which was beyond the scope of this work. Nuclear energy was excluded because we could not reconcile conflicting results of competing assessment approaches (17). To reflect the prospective nature of our inquiry, the modeling of technologies implemented in 2030 and 2050 also contains several assumptions regarding the improved production of aluminum, copper, nickel, iron and steel, metallurgical grade silicon, flat glass, zinc, and clinker (18). These improvements represent an optimistic-realistic development in accordance with predictions and goals of the affected industries, as specified in ref. 18 and summarized in *SI Appendix*, Table S1. Technological progress in the electricity conversion technologies was represented through improved conversion efficiencies, load factors, and next-generation technology adoption to achieve the technology performance of the scenarios (see *SI Appendix* for details).

Results has two parts. First, low-carbon technologies are compared with fossil electricity generation without CCS to quantify environmental cobenefits and tradeoffs relevant for long-term investment decisions in the power sector. This comparison reflects the current state-of-the-art technology performance for both low-carbon and fossil systems. We examine impacts in terms of greenhouse gas (GHG) emissions, eutrophication, particulate-matter formation, and aquatic ecotoxicity resulting from pollutants emitted to air and water throughout the life cycle of each technology. We also compare the life-cycle use of key materials (namely aluminum, iron, copper, and cement), nonrenewable energy, and land for all investigated technologies per unit of electricity produced. *SI Appendix* contains a discussion of technology-specific results. To our knowledge, this analysis is the first to be based on a life-cycle inventory model that includes the feedback of the changing electricity mix and the effects of improvements in background technologies on the production of the energy technologies.

In the second part of *Results*, we show the potential resource requirements and environmental impacts of the evaluated technologies within the BLUE Map scenario and compare these results with those of the Baseline scenario. Our modeling is based on the installation of new capacity and the utilization of this capacity such that it is consistent with the BLUE Map scenario. It traces an important aspect of the transition toward a low-carbon energy system: that new capacity of low-carbon electricity generation technology is constructed using the existing electricity mix at any point of time. We quantify the requirements of bulk materials and the environmental pressures associated with the BLUE Map scenario over time and compare them with the Baseline scenario. We then compare results to annual production levels of these materials. In *Discussion*, we examine issues related to the presented work, in particular the implication of life-cycle effects on the modeling of mitigation scenarios and limitations with respect to the grid integration of variable renewable supply.

Results

Technology Comparison per Unit Generation. Our comparative LCA indicates that renewable energy technologies have significantly lower pollution-related environmental impacts per unit of generation than state-of-the-art coal-fired power plants in all of the impact categories we consider (Fig. 1 and *SI Appendix*, Table S5). Modern natural gas combined cycle (NGCC) plants could also cause very little eutrophication, but they tend to lie between renewable technologies and coal power for climate change (Fig. 1*A*) and ecotoxicity (Fig. 1*C*). NGCC plants also have higher contributions of particulate matter exposure (Fig. 1*B*). The LCA finds that wind and solar power plants tend to require more bulk materials (namely, iron, copper, aluminum, and cement) than coal- and gas-based electricity per unit of generation (Fig. 1 *G–J*). For fossil fuel-based power systems, materials contribute a small fraction to total environmental impacts, corresponding to <1% of GHG emissions for systems without CCS and 2% for systems with CCS. For renewables, however, materials contribute 20–50% of the total impacts, with CSP tower and offshore wind technologies showing the highest shares (*SI Appendix*, Fig. S1). However, the environmental impact of the bulk material requirements of renewable technologies (*SI Appendix*, Table S1) is still small in absolute terms compared with the impact of fuel production and combustion of fossil-based power plants (Fig. 1).

CCS reduces CO_2 emissions of fossil fuel-based power plants but increases life-cycle indicators for particulate matter, ecotoxicity, and eutrophication by 5–60% (Fig. 1 *B–D*). Both postcombustion and precombustion CCS require roughly double the materials of a fossil plant without CCS (Fig. 1 *G–J*). The carbon capture process itself requires energy and therefore reduces efficiency, explaining much of the increase in air pollution and material requirements per unit of generation.

Habitat change is an important cause of biodiversity loss (19). Habitat change depends both on the project location and on the specific area requirement of the technology. For example, PV power may be produced in pristine natural areas (high impact on habitat) or on rooftops (low impact on habitat). A detailed assessment of specific sites used for future power plants is beyond the scope of this global assessment. As an indicator of potential habitat change, we use the area of land occupied during the life cycle of each technology (Fig. 1*E*).

High land-use requirements are associated with hydropower reservoirs, coal mines, and CSP and ground-mounted PV power plants. The lowest land use requirements are for NGCC plants, wind, and roof-mounted PV. We consider roof-mounted PV to have zero direct land use because the land is already in use as a building. For ground-mounted solar power, we consider the entire power plant because the modules or mirrors are so tightly spaced that agriculture and other uses are not feasible in the unoccupied areas. Considering only the space physically occupied by the installation, the area requirements decrease by a factor of 2–3 compared with the values in Fig. 1*E* (8). For direct land use associated with wind power, we consider only the area occupied by the wind turbine itself, access roads, and related installations. We do not include the land between installations because it can be used for other purposes such as agriculture or wilderness, with some restrictions (20). If an entire land-based wind park is considered, land use would be on the order of 50–200 square meter-year/MWh (m^2a/MWh) (8, 20), which is higher than other technologies. We do not account for the use of sea area by offshore wind turbines.

Cumulative nonrenewable (fossil or nuclear) energy consumption is of interest because it traces the input of a class of limited resources. The current technologies used in the production of renewable systems consume 0.1–0.25 kWh of nonrenewable energy for each kWh of electricity produced (Fig. 1*F*). The situation is different for fossil fuel-based systems, for which the cumulative energy consumption reflects the efficiency of power production and the energy costs of the fuel chain and, if applicable, the CCS system.

Scenario Results. The BLUE Map scenario posits an increase in the combined share of solar, wind, and hydropower from 16.5% of total electricity generation in 2010 to 39% in 2050. The required up-front investment in renewable generation capacity

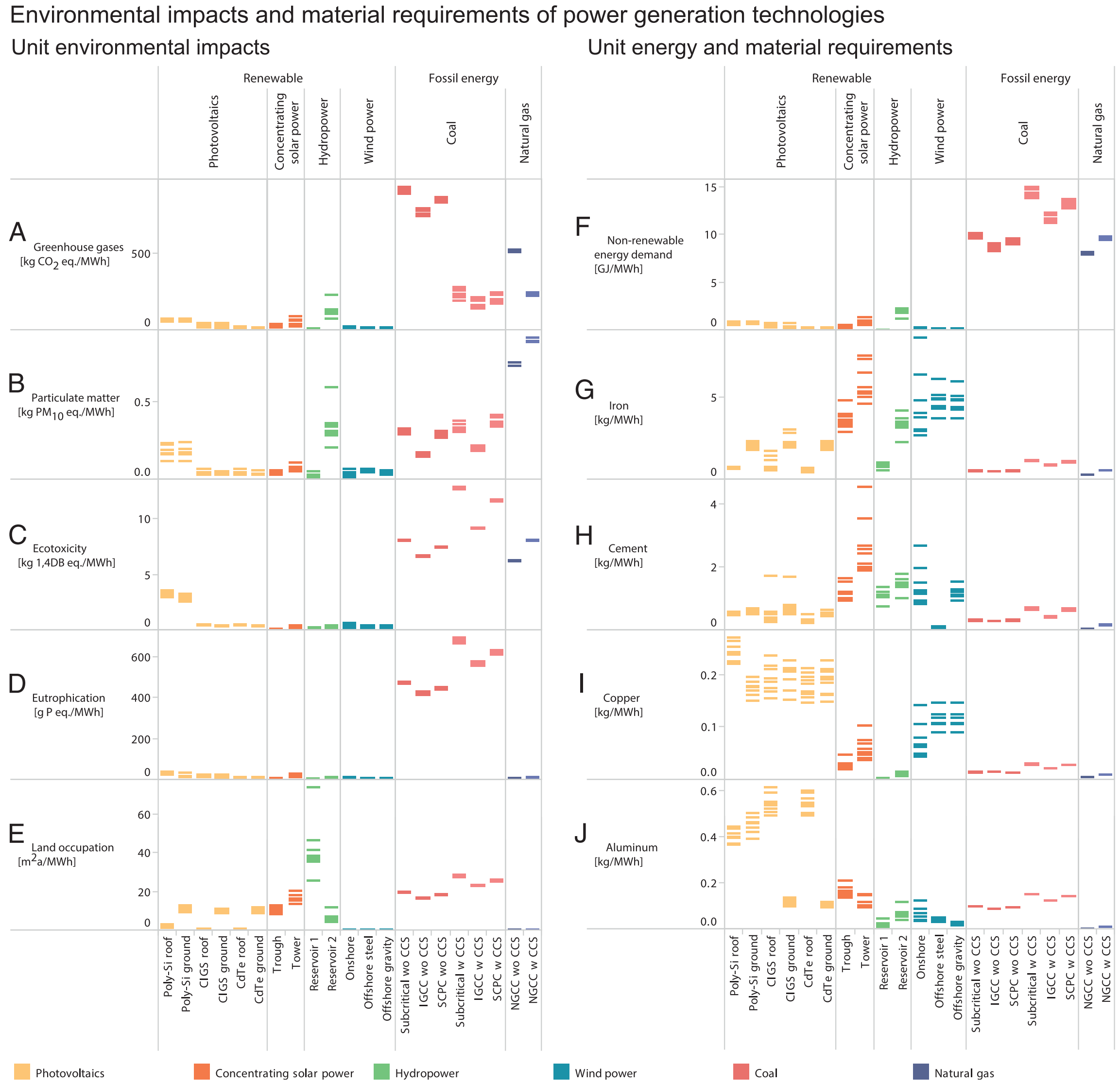

Fig. 1. A comparison of life-cycle environmental pressures and resource use per unit of electricity generated by different power-generation technologies in each of nine world regions. The left column shows four pollution-oriented indicators: (*A*) Greenhouse gases, (*B*) particulate matter exposure, (*C*) freshwater ecotoxicity, and (*D*) freshwater eutrophication. In addition, land occupation (*E*) is shown. The right column indicates nonrenewable primary energy demand (*F*) and the demand for materials (*G*–*J*). CCS, CO_2 capture and storage; CdTe, cadmium telluride; CIGS, copper indium gallium selenide; IGCC, integrated gasification combined cycle coal-fired power plant; NGCC, natural gas combined cycle power plant; offshore gravity, offshore wind power with gravity-based foundation; offshore steel, offshore wind power with steel-based foundation; reservoir 2, type of hydropower reservoir used as a higher estimate; SCPC, supercritical pulverized coal-fired power plant.

would require a combined investment of bulk materials of 1.5 Gt over the period 2010–2050, which is more than the total use of these materials in the Baseline scenario. Because of the need to install new renewable capacity, the material requirement of the BLUE Map scenario is from the outset higher than that of the Baseline scenario, even as the generation profiles are initially quite similar. The difference in material demand displayed in Fig. 2 *G*–*J* shows that the initial demand for iron and cement is mainly associated with wind and CSP installations whereas it is mainly PV driving additional copper demand. The BLUE Map scenario has a lower material demand associated with conventional coal-fired power plants without CCS, which is partly offset by the material demand from coal-fired power plants with CCS. The most important contributor to the material demand from coal-fired power plants is associated with producing and transporting the ∼500 kg of coal required per MWh of electricity generated.

The BLUE Map scenario would be able to keep the emissions of particulate matter and ecotoxicity stable despite the doubling of annual electricity generation from 18 petawatt hours per

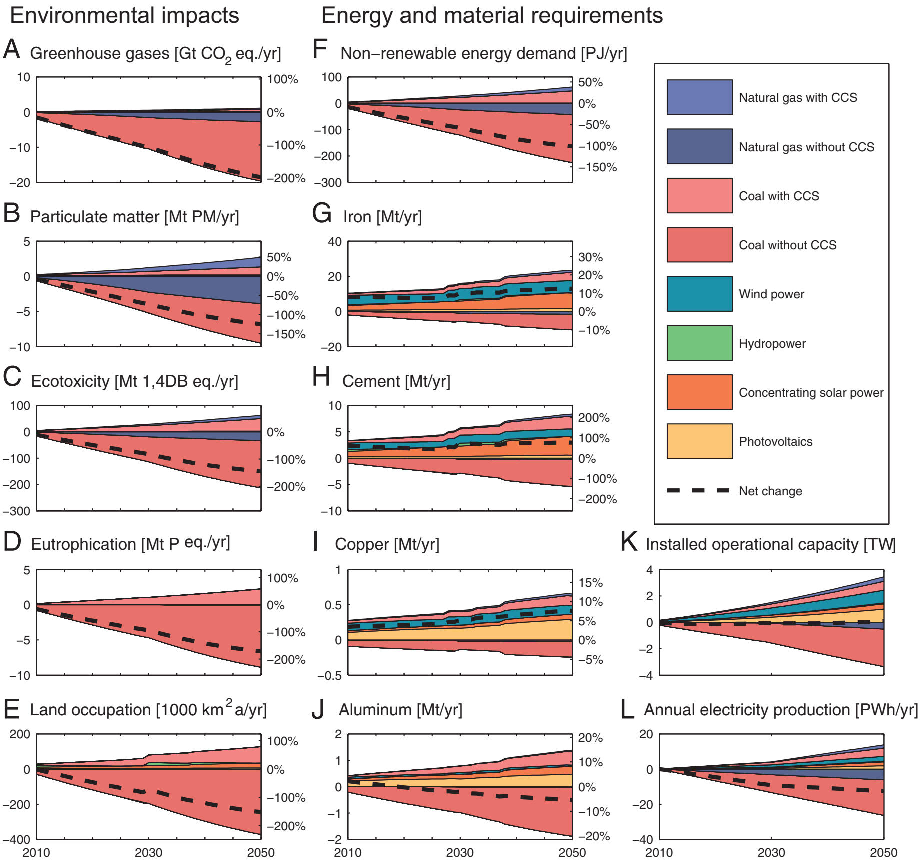

Fig. 2. (*A–L*) Environmental and resource implications of electricity generation following the IEA BLUE Map scenario instead of the IEA Baseline scenario, addressing impacts from the indicated power sources. The results show a reduction of pollution-related environmental impacts despite a doubling of electricity generation but a substantial increase of material consumption, especially copper. Left axes show absolute values. Right axes show the variation, in percentage, between these absolute values and the base levels in 2007. Note that the net change can reach values below −100% when the difference between the Baseline and BLUE Map scenarios is higher than the base 2007 levels.

annum (PWh/a) to 36 PWh/a for the technologies investigated. Compared with the situation in 2010, a substantial reduction in GHG emissions (from 9.4 Gt CO$_2$ eq. to 3.4 Gt CO$_2$ eq.) and eutrophication would be achieved (*SI Appendix*, Fig. S4). In stark contrast, the Baseline scenario would lead to a doubling of all pollution-related indicators even as new, highly efficient coal-fired power plants come online (*SI Appendix*, Fig. S3). The difference in pollution between the BLUE Map and Baseline scenarios would grow dramatically over time (Fig. 2) whereas the additional required material investment would rise only moderately. Such a development is the result of the growing dividend from the continuous investment in renewable generation capacity.

For the BLUE Map scenario, the higher material requirement per unit of renewable electricity and a projected increase in energy demands cause a substantial increase in material use (*SI Appendix*, Fig. S4). The overall material requirement per unit of electricity produced would be 2.3 kg/MWh compared with 1.2 kg/MWh for the Baseline scenario. That increase appears manageable in the context of current production volumes, the long lifetime of the equipment, and the ability to recycle the metals. Compared with material production levels in 2011, the construction and operation of the 2050 electricity system envisioned in the BLUE Map scenario would require less than 20% of the cement, 90% of the iron, 150% of the aluminum, and 200% of the copper, all relative to their respective 2011 production quantities (Table 1). Meeting copper demand could be problematic due to declining ore grades (21), and it would result in potential increases in the environmental costs of copper production (22, 23). Additional evidence for this conclusion is presented in *SI Appendix*.

Displacing fossil fuels through the widespread deployment of solar and wind energy could limit air and water pollution (Fig. 2). Over the study period (2010–2050), emissions of GHG connected to the power plants investigated are 62% lower in BLUE Map than they are in the Baseline Scenario whereas the particulate matter is 40% lower, freshwater ecotoxicity is almost 50% lower, and eutrophication is 55% lower. Furthermore, both cumulative energy consumption and land use are reduced. Our analysis might understate the cobenefits of climate-change mitigation in the form of pollution reduction because we assume the replacement of state-of-the-art fossil power plants with well-operating, modern emissions control equipment; the actual situation might be that emissions control equipment are functioning suboptimally or are altogether absent due to a lack of regulation.

Table 1. Cumulative material requirements for electricity production for the BLUE Map scenario

Material	Annual production (2011), Gt	Metal requirements to 2050, Gt	Ratio
Aluminum	0.045	0.067	1.5
Copper	0.013	0.029	2.2
Iron	1.5	1.3	0.87
Cement	3.4	0.52	0.15

The middle column provides an estimate of the volumes of materials that need to be produced to provide for the capital stock additions between 2010 and 2050 and the material requirements associated with operational inputs (fuels, transport, solvents, etc.) during the same period. The right hand column expresses these material requirements as a fraction of the 2011 production volume.

Further results on specific technologies, GHG emissions from material production, and the scenario analysis are presented in *SI Appendix*.

Discussion

Previous assessments of life-cycle impacts of electricity-generation technologies have used static LCAs (7, 11–15). Technologies are thus analyzed side-by-side, assuming current production technologies. We present an assessment based on an integrated, scenario-based hybrid LCA model with global coverage through the integration of the life-cycle process description in a nine-region multiregional input–output model. Integration of the life-cycle model, in which new technologies become part of the electricity mix and thus the life cycle of the same and other new technologies, addresses the interaction among technologies. Adopting a vintage capital model, the life-cycle stages of individual power plants are explicitly in time, also a novelty compared with current LCA practice. This previously unidentified type of modeling approach thus provides the ability to model the role of various technologies in a collectively exhaustive and mutually exclusive way. Only through this integration can the life-cycle emissions and resource use of energy scenarios be analyzed correctly. Further, we can assess the contributions of changes in the technology mix and improvements in the technology itself to future reductions of environmental impacts, as demonstrated in ref. 24.

The widespread utilization of variable sources such as solar and wind energy raises the question: what are the additional environmental costs of matching supply and demand? Grid-integration measures for variable supply, such as the stand-by operation of fossil fuel power plants, grid expansion, demand-response and energy storage (25–27), result in extra resource requirements and environmental impacts (28). The challenges of balancing supply and demand are not yet severe in the BLUE Map scenario, in which variable wind and solar technologies cover 24% of the total electricity production in 2050, but balancing becomes a serious concern later in the century in the many mitigation scenarios investigated by ref. 2 that rely on a higher share of variable renewables. In the BLUE Map scenario, the capacity factor of fossil fuel-fired power plants without CCS is reduced from 40% in 2007 to 19% in 2050 for natural gas, and from 65% to 30% for coal for the same period, but IEA provides no information on emissions associated with spinning reserves, or ramp-up and ramp-down. The National Renewable Energy Laboratory's (NREL) Western Wind and Solar Integration Study indicates that increased fossil power plant cycling from the integration of a similar share of variable renewables may result in only negligible increases in greenhouse gas emissions compared with a scenario without renewables. It may also result in further reductions in nitrogen oxide emissions and increases in SO_2 emissions equal to about 2–5% of the total emissions reduced by using renewables. In a study investigating an 80% emission reduction in California, electricity storage requirements become significant only at higher rates of renewable energy penetration (26). See *SI Appendix* for further information on grid integration of renewables. Additional research on different options for the system integration of renewables and its environmental impact is required to determine the share of renewables most desirable from an environmental perspective.

Our analysis raises important questions. (*i*) What would similar analyses of other mitigation scenarios look like? Thousands of scenarios have been collected in the Intergovernmental Panel on Climate Change (IPCC) mitigation scenario analysis database (4). These scenarios use a combination of energy conservation, renewable and nuclear energy, and CCS. Our analysis suggests that an electricity supply system with a high share of wind energy, solar energy, and hydropower would lead to lower environmental impacts than a system with a high share of CCS. (*ii*) How can scenarios for a wider range of environmental impacts be routinely assessed? Endogenous treatment of equipment life cycles as considered here in energy-scenario models has not yet been achieved. Options are either to (*a*) include some simplified assessments in energy scenario models, using the unit-based results from our analysis in the scenario models, or to (*b*) conduct a postprocessing of scenario results in the manner done for this study. The advantage of option *a* is that life-cycle emissions could be considered in the scenario development, thus affecting the technology choice; the advantage of option *b* is the ability to include feedbacks and economy-wide effects in the calculation of life-cycle emissions. (*iii*) Will fundamental differences in energy systems such as those between mitigation and baseline scenarios lead to significant changes to the supply and demand for many products (e.g., fuels and raw materials)? It is clear that there will be effects on the supply and demand of goods both due to different energy policies (e.g., carbon prices) and because of differences in the demand and supply of resources (e.g., iron or coal) to the global economy. Such indirect effects were outside of the scope of this study, but they could be considered in a consequential analysis (29).

Conclusions

Our analysis indicates that the large-scale implementation of wind, PV, and CSP has the potential to reduce pollution-related environmental impacts of electricity production, such as GHG emissions, freshwater ecotoxicity, eutrophication, and particulate-matter exposure. The pollution caused by higher material requirements of these technologies is small compared with the direct emissions of fossil fuel-fired power plants. Bulk material requirements appear manageable but not negligible compared with the current production rates for these materials. Copper is the only material covered in our analysis for which supply may be a concern.

Materials and Methods

Using a uniform data-collection form, we collected foreground data describing the life-cycle inventory of the analyzed technologies. For more information on inventory data and modeling assumptions, see *SI Appendix*. These foreground data were linked to the ecoinvent 2.2 life-cycle inventory database (30), which provides information on many input processes such as materials and manufacturing, and the EXIOBASE input–output database (31), which provides emissions estimates for inputs of services and highly manufactured goods. We modeled nine world regions to perform a regional sensitivity analysis. Exogenous scenario parameters and electricity mixes were taken from the IEA scenarios (16), which represent the same nine world regions. Impact assessment was conducted using ReCiPe version 1.08 (32). To specify resource use, cumulative nonrenewable energy demand, land use, and the use of iron, aluminum, and copper (metal content of the ore or scrap used) were specified. To complement environmentally important material flows (33), we also quantified the amount of cement required. Life-cycle inventories for this comparative analysis were built based on our original work and a review of scientific literature on the selected technologies. To obtain a better representation of the fugitive methane emissions related to fossil-fuel extraction, ecoinvent 2.2 was updated with the fugitive emissions factors published in ref. 34, which is in line with other recent estimates.

To develop the scenarios of emissions and resource use presented in Fig. 2 and *SI Appendix*, Figs. S3 and S4, we identified the timing of capacity additions, operations, repowering, and removal of power plants in the scenario (35). We delineated the life-cycle impacts into these phases. Therefore, the figures reflect the timing of resource use and emissions, not the timing of electricity generation. The inventories associated with each life cycle step reflect the technology status and electricity mix of the year in question. The IEA provides electricity production by technology group (e.g., PV), so we estimated intratechnology group market shares [e.g., the division of the PV market among Si, cadmium telluride (CdTe), and copper indium gallium selenide (CIGS) technologies]. As of 2010, 90% of the PV market in terms of produced electricity was silicon-based whereas the remaining share consisted of thin-film modules. The share of silicon-based modules gradually decreases to 20% in 2050. Half of the electricity produced by CSP was assumed to be generated from central receivers systems; the other half was assumed to be from parabolic troughs. This allocation remained consistent throughout the scenario time frame. Hydropower plants were represented by two different dams modeled after the Baker River Basin dams in Chile. Unit results show high variability, even within the same river basin. Wind power plants were assumed to contain conventional gearbox-equipped wind turbines because reliable LCA data on rare earth metal use in direct drive wind turbines could not be obtained. Offshore wind farm production was modeled as an even mix of gravity-based and steel foundation turbines. The market mix of coal-combustion technologies was modeled after real production data for China, India, and the United States. A global average was applied for other regions. Due to high uncertainty of coal market share estimates, we used the 2010 mix for 2030 and 2050. We assumed all gas-fired power plants used combined cycle technology.

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Supporting Information (SI)

Title:

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

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Contents

MATERIALS AND METHODS

Goal and scope

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

Inventory data structure

IEA Energy Technology Perspectives Scenarios

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

Energy technology product systems (foreground)

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

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

Life cycle inventory database (background)

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

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

Multiregional input-output model (background)

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

Impact assessment

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

Resource assessment

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

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

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

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

Model description

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

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

General model characteristics

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

General model structure

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

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

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

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

Vintage capital modeling

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

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

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

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

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

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

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

Scenario-based assumptions about the improvement of background technologies

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

Life cycle inventories of energy technologies

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

Photovoltaics

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

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

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

Concentrating solar power

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

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

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

Hydropower

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

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

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

Wind power

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

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

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

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

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

Fossil fuel based power with and without carbon capture and storage

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

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

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

ADDITIONAL RESULTS AND DISCUSSION

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

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

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

Technology-level results

Photovoltaics

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

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

Permanent URL:

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

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

Concentrating solar power

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

Hydropower

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

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

Wind power

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

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

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

Coal

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

Natural gas

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

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

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

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

Critical materials

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

Reliability and uncertainty of the results

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

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

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

Grid balancing

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

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

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

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

IMPLICATIONS FOR FURTHER RESEARCH

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

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

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APPENDIX 1: TABLES

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

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

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

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

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

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

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

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

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

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

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

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

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

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

APPENDIX 2: FIGURES

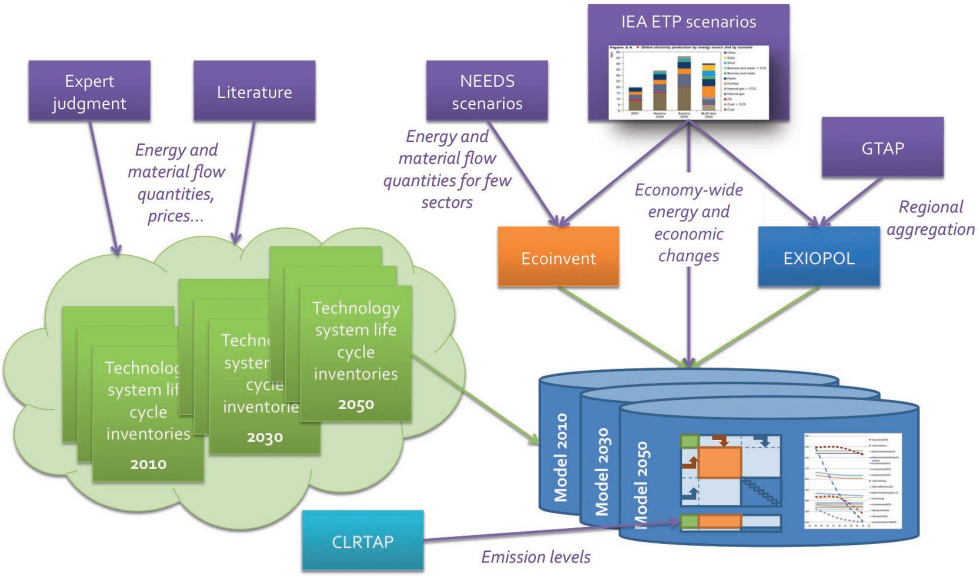

Figure S1: Flowchart of the different flows of information and data in the model. Green arrows represent base data; purple arrows represent external information that modifies these base data. NEEDS–New Energy Externalities Development for Sustainability. IEA ETP–International Energy Agency's Energy Technology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

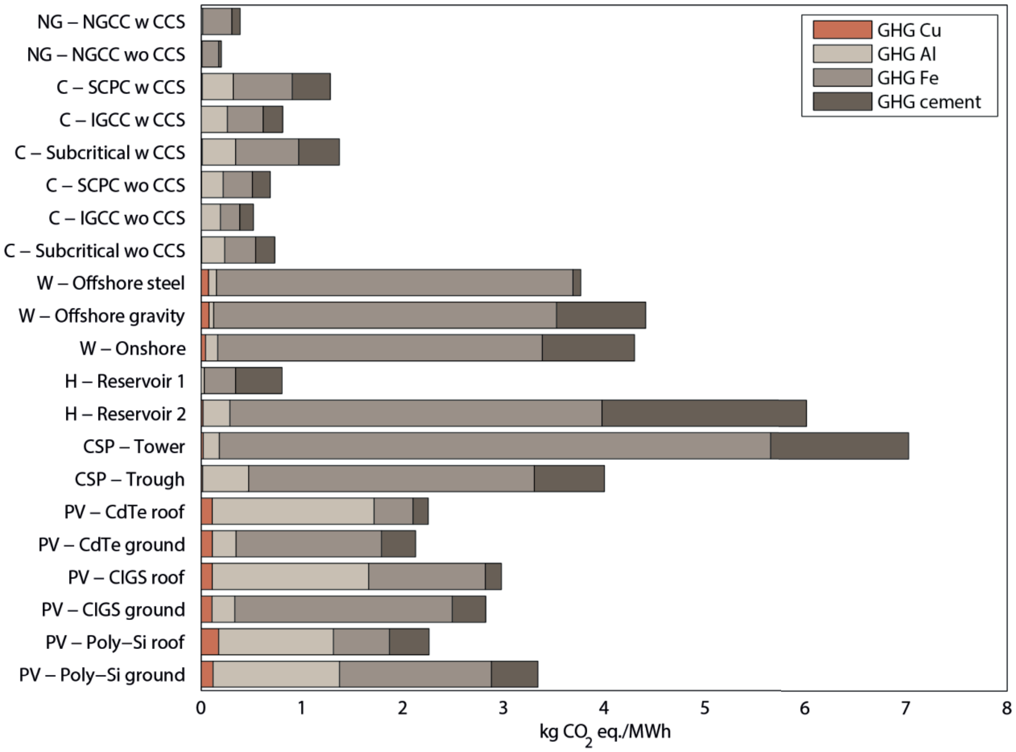

Figure S2: GHG emissions associated with the production of bulk materials for each of the investigated technologies. Abbreviations: PV–photovoltaics, CSP–concentrating solar power, H–hydropower, W–wind power, C–coal, NG–natural gas, Poly-Si–polycrystalline silicon, CIGS–copper indium gallium selenide,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

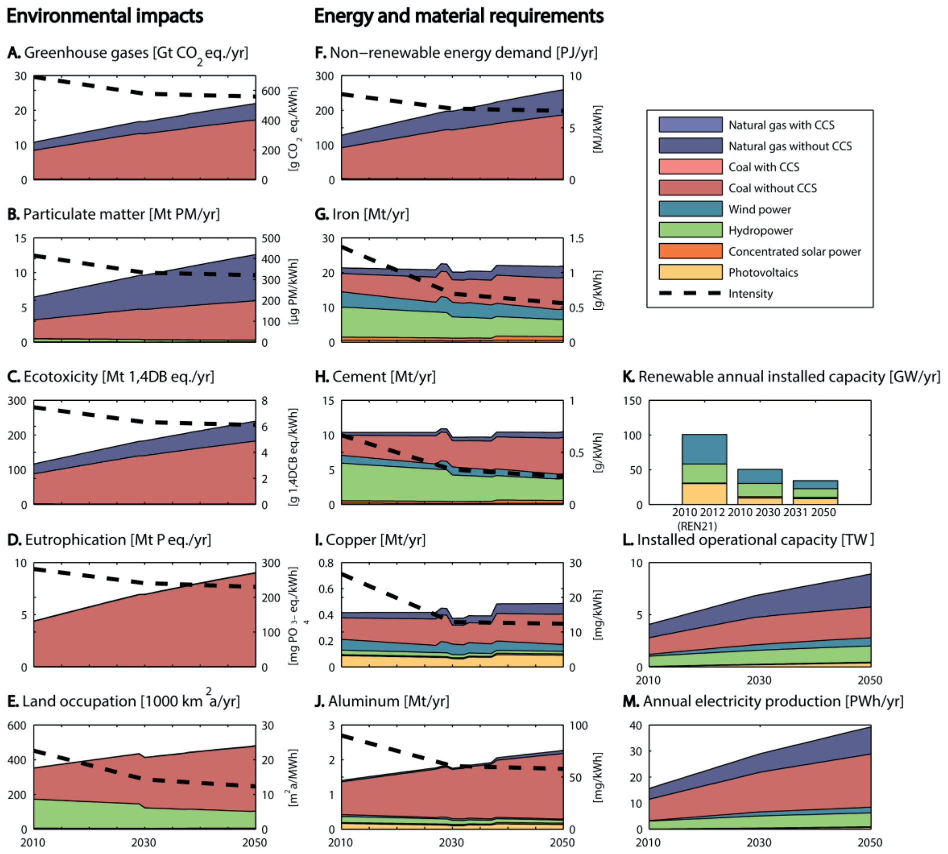

Figure S3: Midpoint indicators, energy and material requirements, absolute, for the IEA baseline scenario. Left: greenhouse gas, particulate matter, freshwater ecotoxicity and eutrophication, and land use. Middle: non-renewable cumulative energy demand, iron, cement, copper and aluminum requirements.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

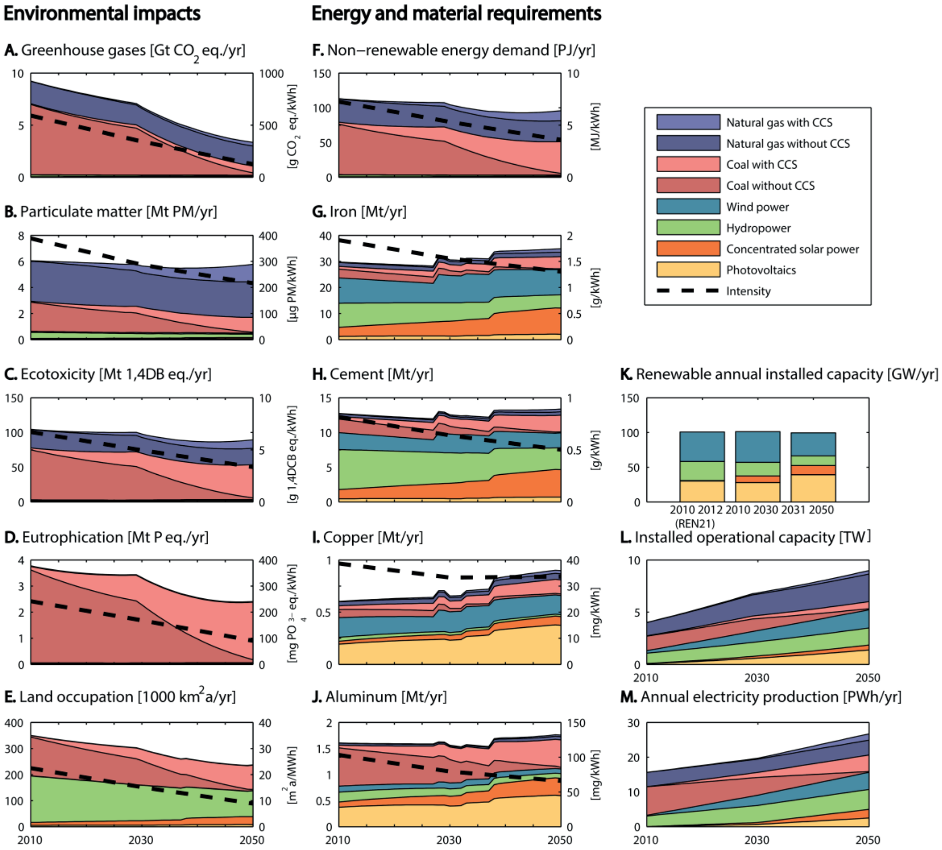

Figure S4: Midpoint indicators, energy and material requirements, absolute, for the IEA BLUE Map scenario. Left: greenhouse gas, particulate matter, freshwater ecotoxicity and eutrophication, and land use. Middle: non-renewable cumulative energy demand, iron, cement, copper and aluminum requirements.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

PAPER III

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Health benefits, ecological threats of low-carbon electricity

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Keywords: energy scenario, LCA, consequential life cycle assessment, integrated hybrid life cycle assessment, biomass energy, climate change mitigation, ecosystem impact

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.

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**

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 [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.

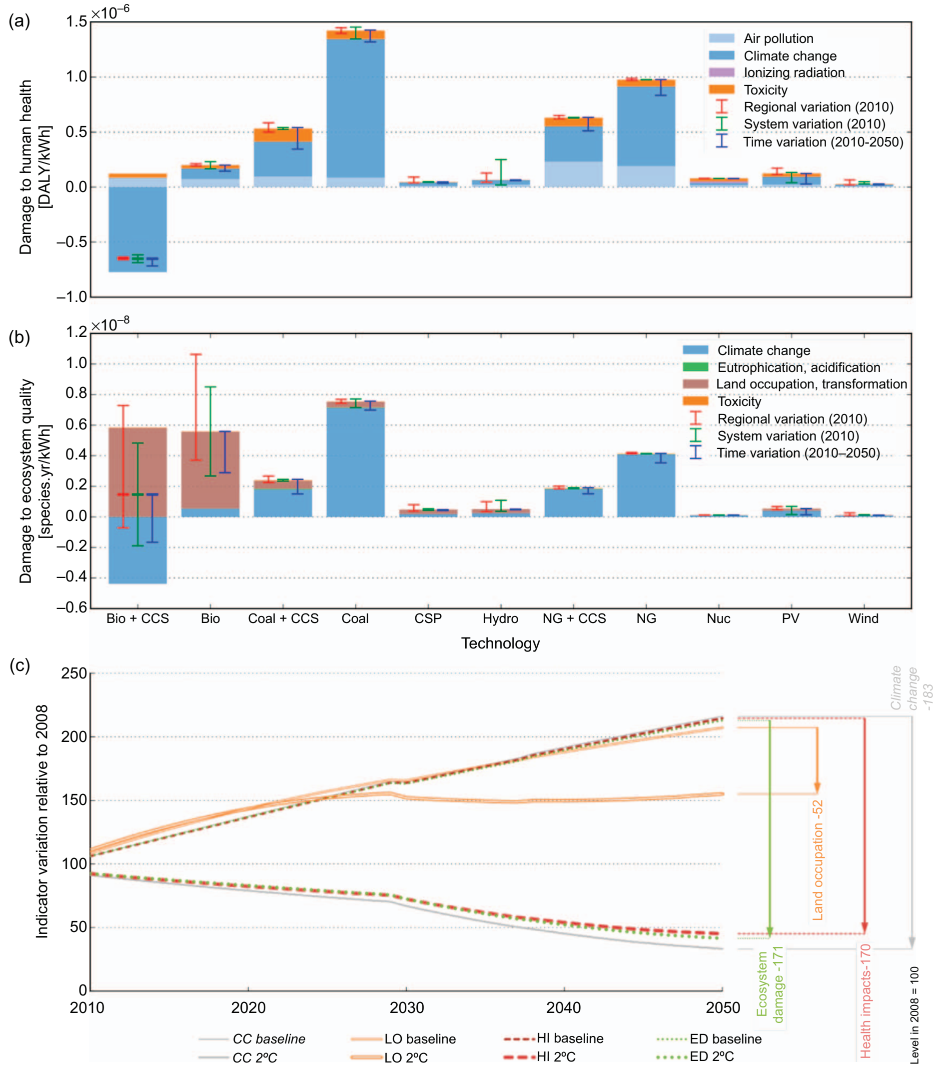

Figure 1. Unit results for the damage to human health (*a*) and ecosystem quality (*b*) of one kilowatt-hour of global mix electricity at grid. Environmental impacts from 2010 to 2050 following 2 °C and baseline scenarios (*c*), displaying human health, ecosystem quality, as well as indicators for greenhouse 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

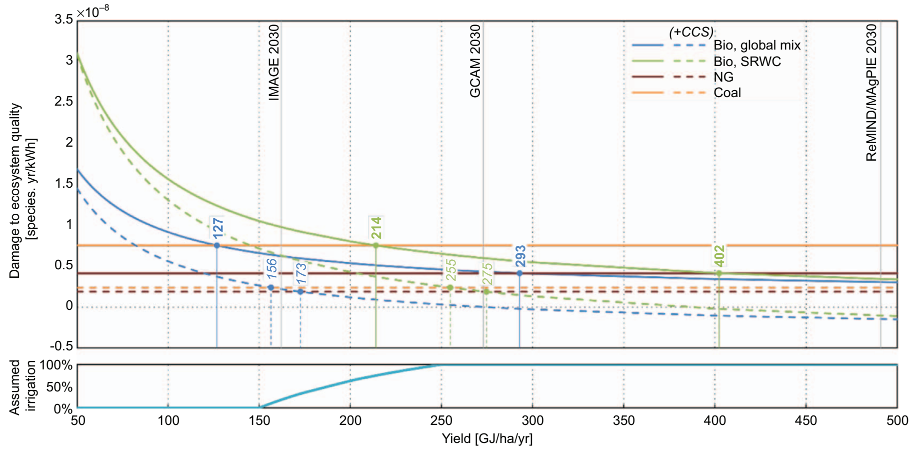

Figure 2. Influence of the energy yield, in GJ ha^{-1} yr^{-1}, on the ecosystem damage score of biopower technologies, in species.yr/kWh. Break-even values are shown for yields that bring the impact of biopower equal to that of coal or gas, with and without CCS. The 2030 value of three different models 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^{2}a 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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PAPER III, SUPPLEMENTARY INFORMATION

The following appendix to Paper III (4 pages) is available online at

http://iopscience.iop.org/1748-9326/12/3/034023/media/erlaa6047_suppdata.pdf

Supplementary Material

Figures S1-S3

Supplementary Text

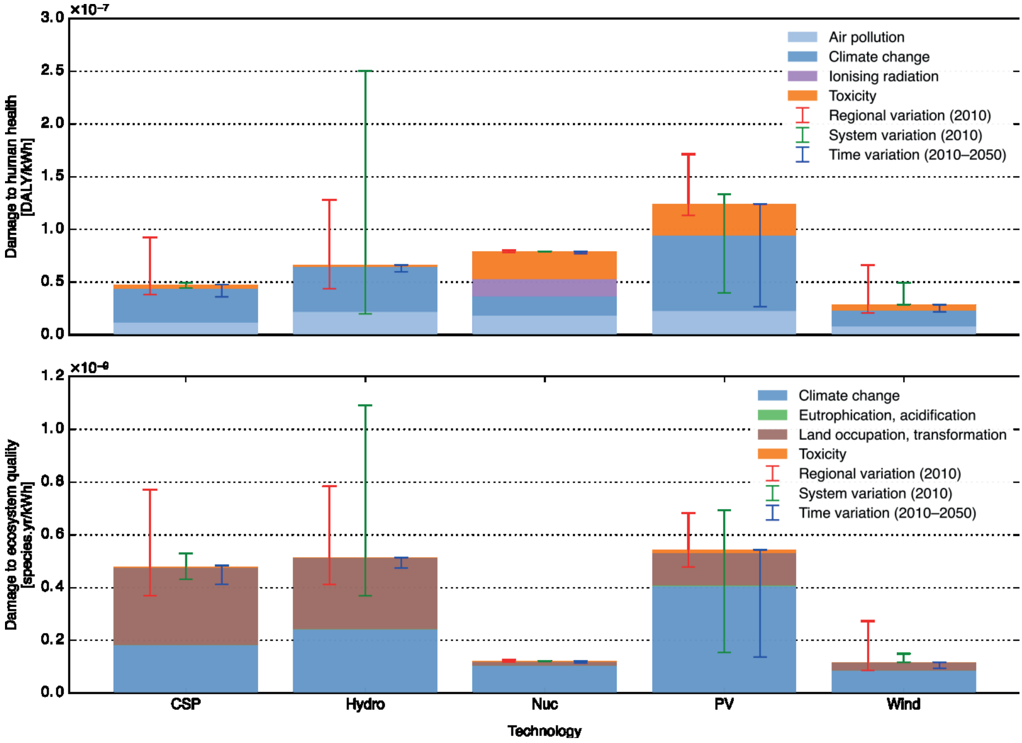

Fig. S1. *Damage to human health and ecosystem quality of 1 kWh of electricity from low-carbon energy technologies. Similar to Panels A and B in the main figure, with only non-combustion technologies. CSP: Concentrating solar power, Nuc: nuclear fission, PV: photovoltaics.*

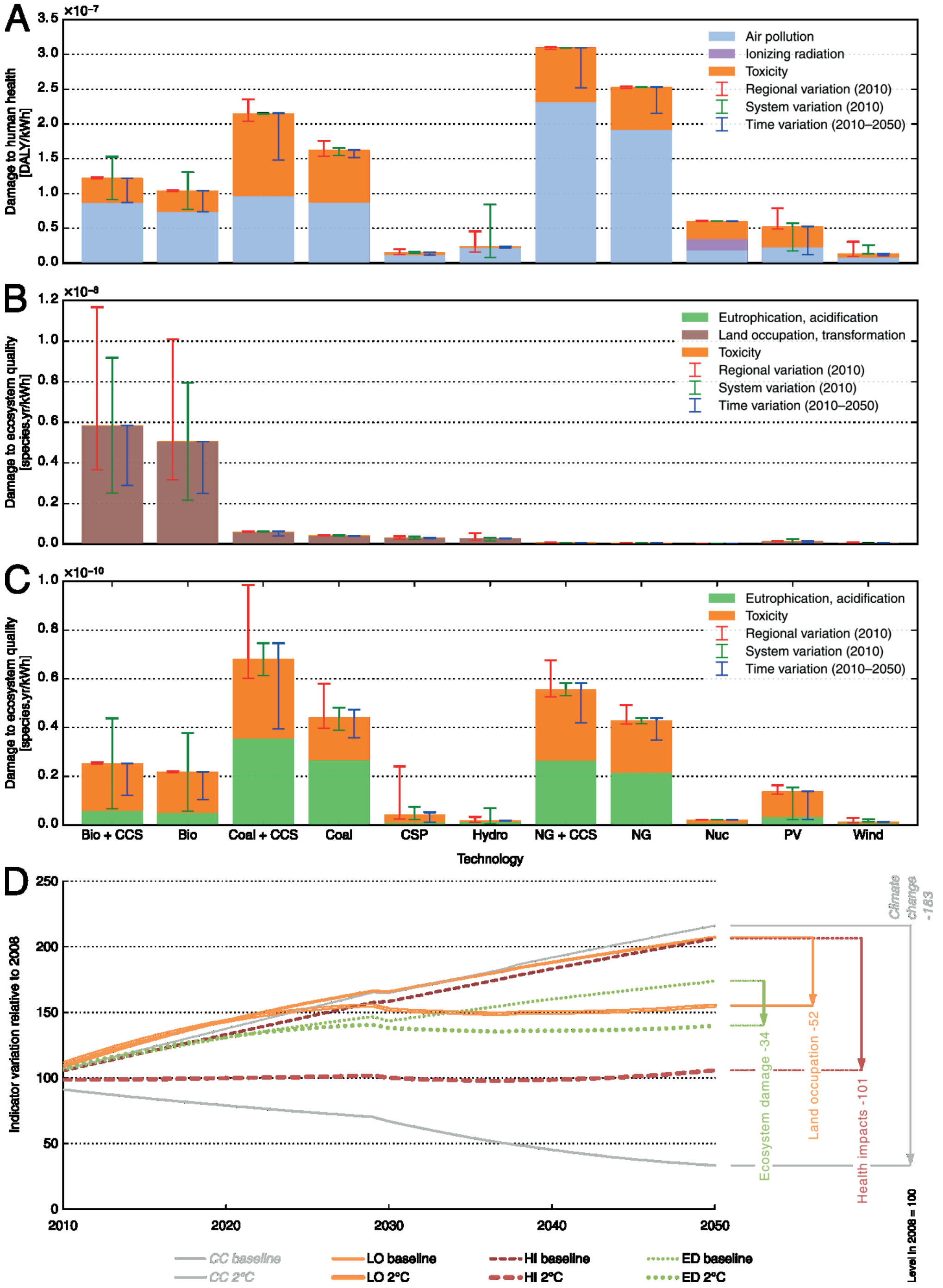

Fig. S2. A, B and C: Unit results for the damage to human health and ecosystem quality of one kilowatt-hour of global mix electricity at grid, excluding the contribution of climate change, and of land occupation in C only. D: Variation of endpoint (damage to human health, ecosystem quality, as "health impacts" and "ecosystem damage" respectively) and midpoint (climate change, land occupation) indicators for the global electricity production (photovoltaic; concentrating solar power; hydropower; wind power; nuclear, as well as coal, gas and biomass with and without carbon dioxide capture and storage) from 2010 to 2050.

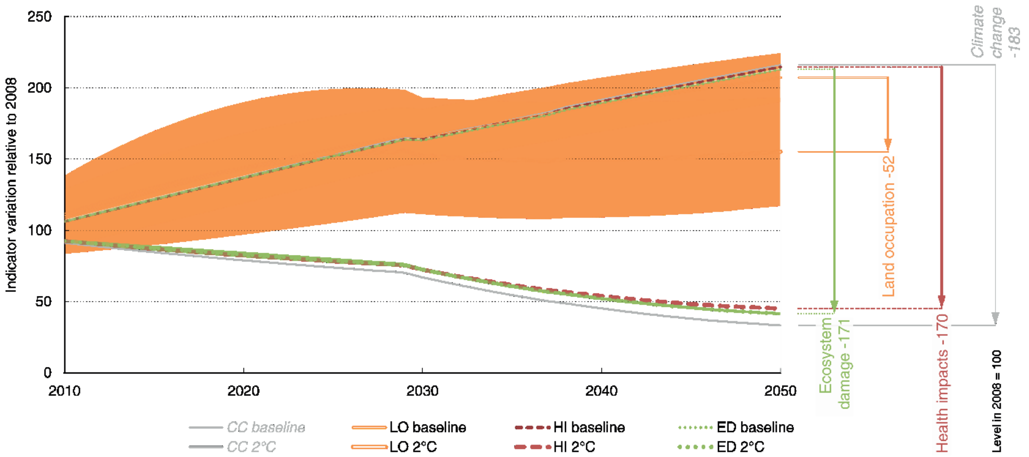

Fig. S3. *Environmental impacts from 2010 to 2050 following 2 °C and baseline scenarios, displaying human health, ecosystem quality, as well as indicators for greenhouse gas emissions, land occupation, which are the two most important environmental mechanisms. Error bands are shown for land occupation and ecosystem damage to represent the range of impacts depending on biopower feedstock, from 100% residues (lower end of error bands) to 100% short rotation wood crops (higher end). All global results are based on a weighted average of regional production by more specific technological system. CC: climate change (measured by* CO_2 *equivalents), LO: land occupation, HI: human health impact, ED: ecosystem damage.*

Supplementary results

Supplementary figures

Figures S1-S3 shed more detailed insights into the analysis presented in the main text.

Fig. S1 displays more detail for the low impacts of low-carbon technologies not involving combustion. Climate change remained dominant even for those technologies, mainly due to energy-intensive plant construction. The impacts of solar technologies varied across regions reflecting the variation in direct normal insolation (DNI). System variation was the highest for hydropower, due to high site-specificity. Finally, photovoltaics (PV) offered the most drastic impact reduction over time, as a shift from energy-intensive polycrystalline silicon to thin-film modules was assumed throughout the 2010–2050 period[25].

To emphasize the issue of co-benefits and adverse side effects, Fig. S2 excludes the impacts from climate change, and for panel C also from land use. Panel A highlights the contribution of air pollution and toxicity to the damage to human health. Panel B highlights the impact of land occupation and transformation to the damage to ecosystem quality. Combustion technologies emitted a significant share of particulate matter and photo-oxidant formation substances that contribution contribute to air pollution (Fig. S2, Panel A), while the extraction and transportation of energy carriers contribute the most to toxicity (Fig. S2, Panels A and C). With CCS, all these emissions increased because of an energy penalty. Excluding the contribution of climate change, land occupation or transformation in Panel C, fossil fuels showed the largest impacts on ecosystem quality, almost equally split between toxicity and eutrophication/acidification. For renewable and nuclear electricity, toxicity, mostly related to material production, tended to be predominant for the low-carbon technologies. The eutrophying effects of nitrogen emissions from biomass feedstocks' cultivation were quantified but not represented in our model because the impact assessment methodology (ReCiPe 1.08) does not characterize marine eutrophication at the endpoint level. The two biopower technology systems would contribute significantly to marine eutrophication.

The scenario results for impacts excluding climate change in Fig. S2, Panel D showed that the 2 °C scenario had lower impacts than the baseline scenario, indicating clear co-benefits of climate change mitigation. The gains are modest, however. Human health impacts remain constant in the 2 °C scenario in spite of the aggressive implementation of clean technologies, and ecosystem impacts still increase, even though more modestly than under the baseline scenario. In the 2 °C scenario, biopower increases to a modest 4% of installed capacity, versus 2% for the baseline. A more aggressive utilization of biopower with CSS after 2050, as foreseen in most 2 °C scenarios investigated by the IPCC[71], would lead to steeper increases in ecosystem impacts. The rising electricity consumption in both scenarios until 2050 is an important reason for this disappointing development in ecosystem impacts. It remains to be seen whether a systematic consideration of total impacts in technology choice instead of a focus only on CO_2 emissions can yield more co-benefits and thus reduce non-climate impacts of electricity generation.

Fig. S3 shows how sensitive environmental and health impacts are to the choice of biopower feedstock. Our main analysis assumes that global biopower uses 50% of forest residues and 50% of short rotation wood crops. To capture the influence of a variable mix different than 50%/50%, the error bands on Fig. S3 show the extent of impacts due to a potential feedstock mix variation, ranging from 100% of forest residues to 100% of SRWC. Using more forest residues than SRWC would tend to lower the stress on land occupation significantly, as well as the resulting ecosystem damage, yet to a much lower extent (1%-3%). Fig. S3 highlights the higher dependence of 2°C scenario on biopower: it can be observed that land occupation is subject to more potential feedstock-dependent variation. Remarkably, a large change in land occupation has little effect on ecosystem diversity overall, as most of the total impact is the result of a high share of coal-fired electricity combined with a high per-kWh impact, dominated by greenhouse gas emissions.

PAPER IV

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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 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 [45] 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) [45]. 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 [46] and the Millennium Ecosystem Assessment [47], see also [7].

3. Results

An overview of LCA results for all investigated technologies and indicators is provided in Fig. 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 [48]. 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 [49,50]. The introduction of supercritical and ultrasupercritical coal power plants is a significant recent development that has raised the efficiency from 35% to 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 [51–53]. 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 (Fig. 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 (Fig. 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 Fig. 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. [54] implemented in this work. Analyses based on European fuel mixes [55] 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 [56,57]. 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 [58]. 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 [59]. 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 Fig. 1 shows,

Fig. 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.

but impact are generally lower than those of the 2010 global mix of electricity [44], with the exception of land use and metal depletion. Fig. 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 [60,61]. 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 [62]. 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 (Fig. 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 Fig. 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 (Fig. 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 [63]. The impacts of ground-mounted and roof-mounted systems are similar, but different elements contribute (Fig. 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 64–97% of all environmental impacts assessed except for the impact on land occupation, which is mostly caused by the infrastructure (Fig. 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 [64], 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) [40,65], 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) (Fig. 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 [66]. 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 (Fig. S9). This is due to the high geogenic emissions: 83 g CO_2/kWh [67], 0.1587 g SO_2/kWh [68], 0.75 g CH_4/kWh, 0.06 g NH_3/kWh [69] and 4 g Hg/MWh [70]. 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 [71].

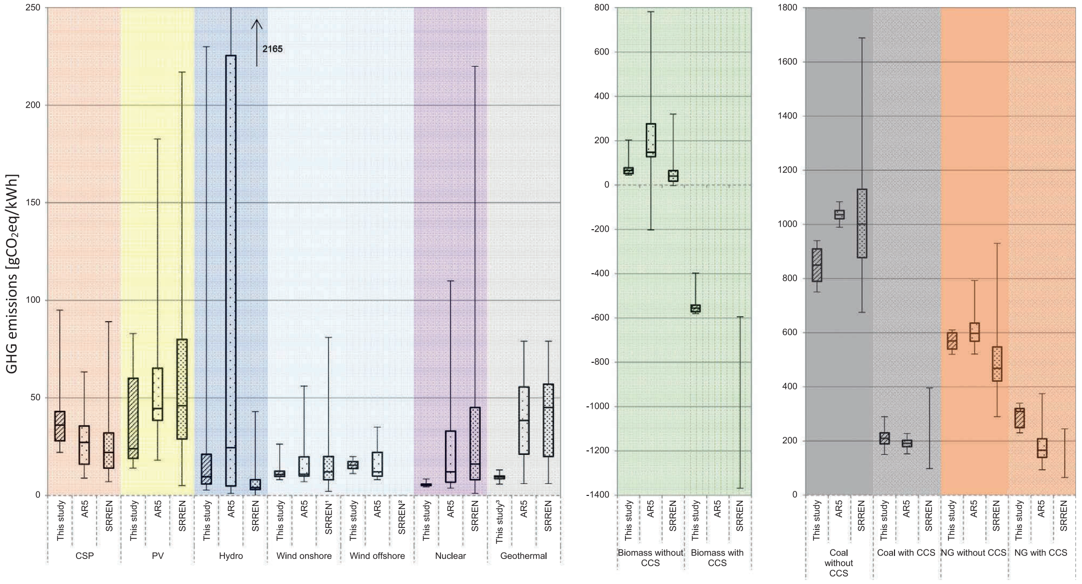

Fig. 2. Comparison of life cycle greenhouse gas emissions (g CO_2 eq./kW h) between this study's results, the IPCC Fifth Assessment Report (AR5) [1], and Special Report on Renewable Energy Sources and Climate Change Mitigation (SRREN) [3,8]. Low-carbon electricity production technologies are shown in 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.

3.10. Comparison of life cycle greenhouse gas emissions

In Fig. 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 [11,72]. 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 modeling 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 [73,74]. For some technologies, the consequences of accidents may be as large as those of routine operations, for example for nuclear power [75]. Efforts to integrate the implication of accidents are hence welcome [74].

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.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.rser.2017.03.078.

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PAPER IV, SUPPLEMENTARY INFORMATION

The following appendix to Paper IV (11 pages) is available online at

http://ars.els-cdn.com/content/image/1-s2.0-S1364032117304215-mmc2.docx

Supporting Information to
"Life Cycle Assessment of Low-Carbon Electricity Supply Options"

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Additional results

Coal

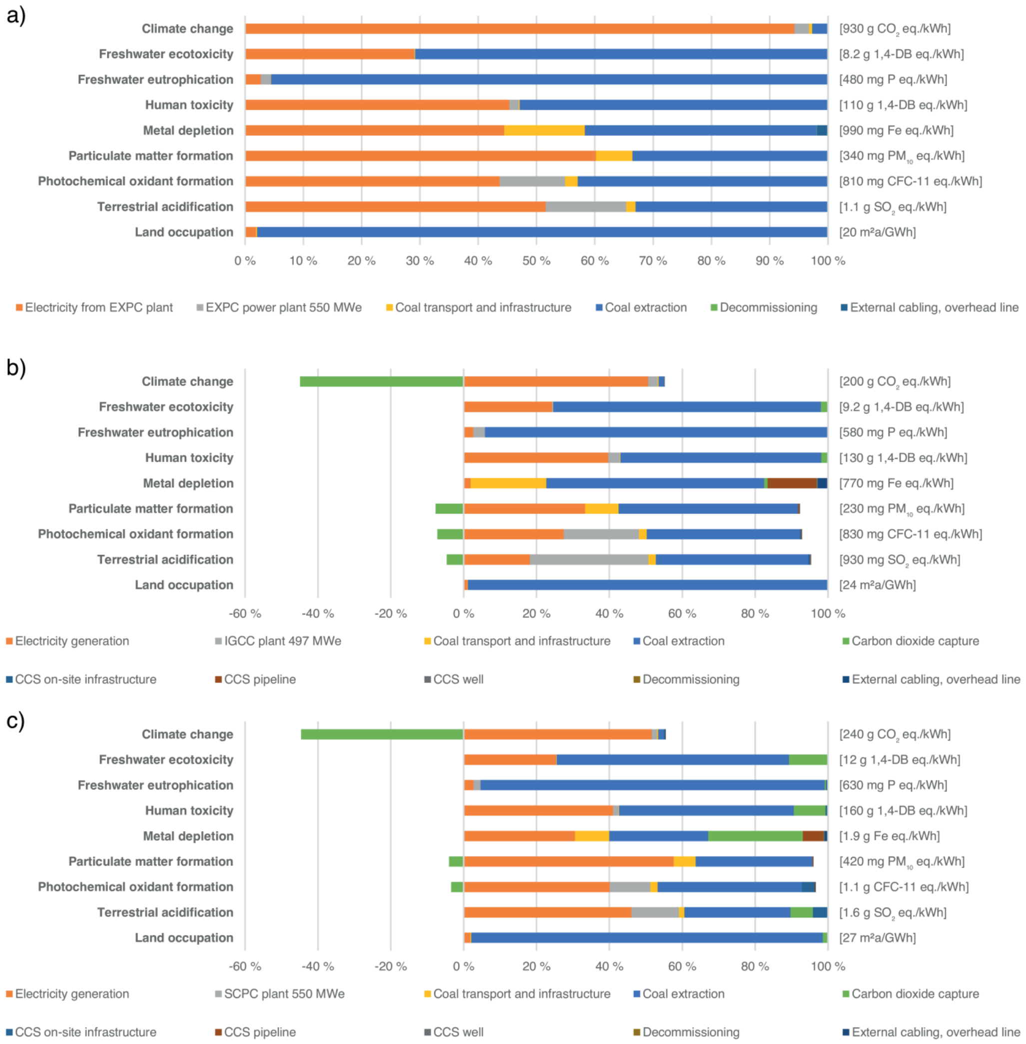

Figure S1: Contribution analysis of coal fired power plants: a) subcritical, b) IGCC with CO_2 capture and storage (CCS) c) supercritical with CCS. Location: China.

Natural gas

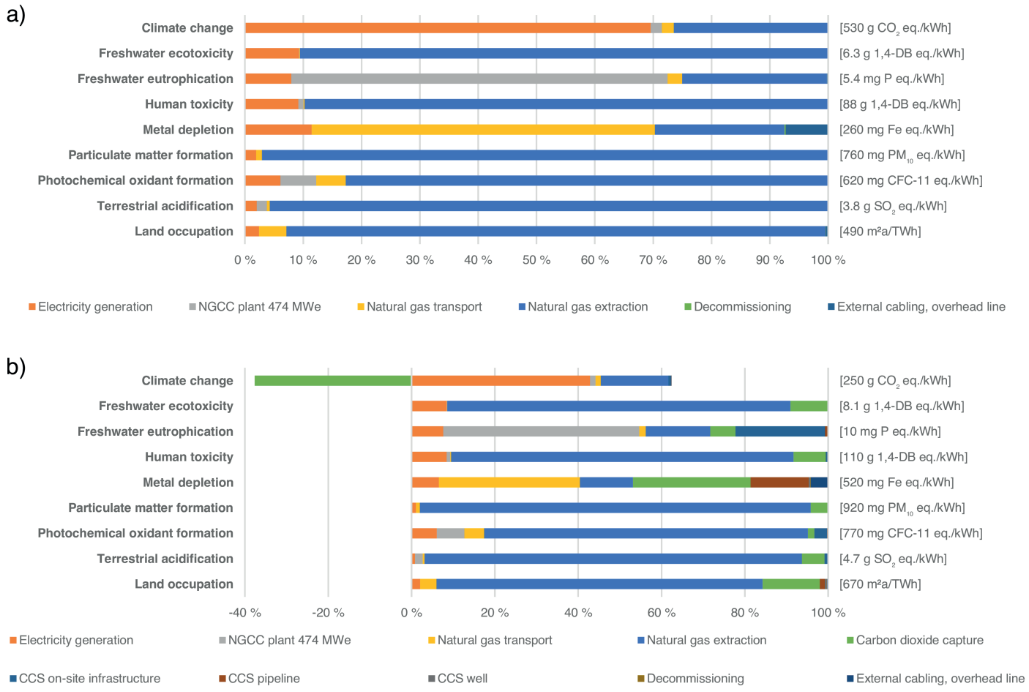

Figure S2: Contribution analysis of natural gas fired power plants: a) natural gas combined cycle without CCS and b) with CCS. Location: China.

Hydropower

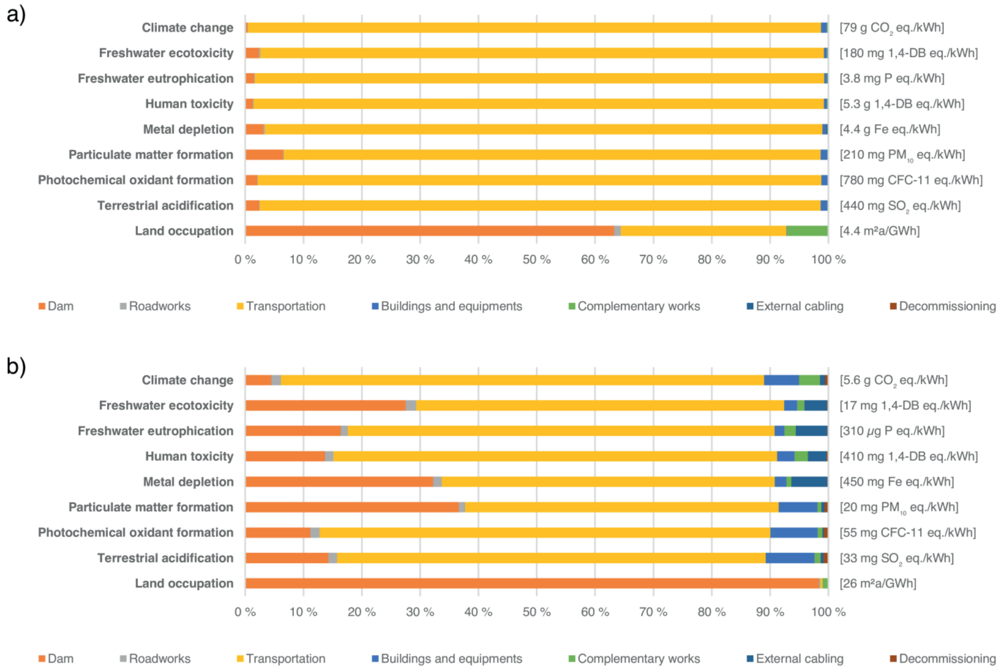

Figure S3: Contribution analysis of hydropower plants: a) 660 MW b) 360 MW dams. Location: Chile (Baker 1 and 2). The inventory reflects a Latin American background economy.

Wind power

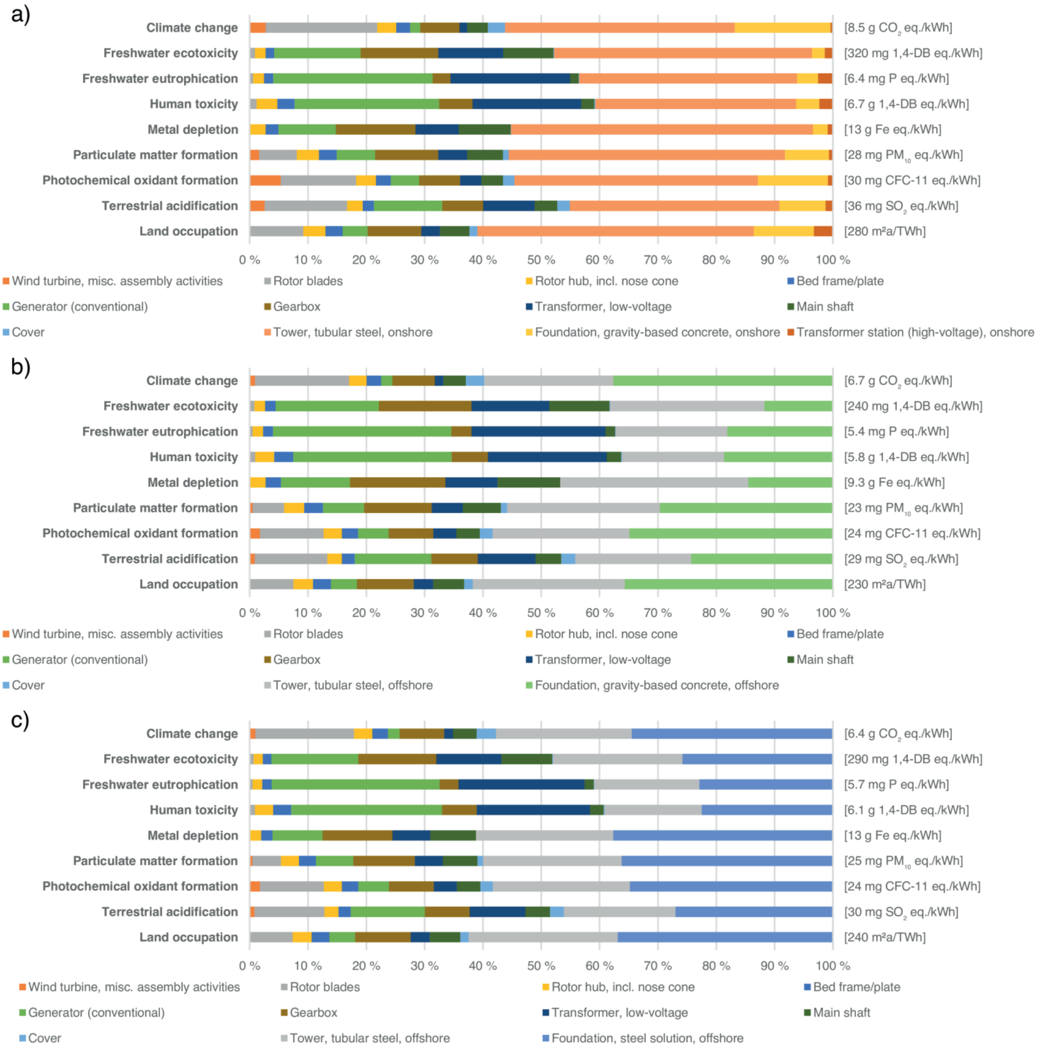

Figure S4: Contribution analysis of wind power plants: a) onshore, and b) gravity-based (concrete) and c) steel foundations offshore wind power systems. Turbines are produced and located in OECD Europe.

Concentrated solar power

Figure S5: Contribution analysis of concentrated solar power: a) parabolic trough and b) central tower plants, under Africa & Middle East conditions (2400 kWh/m^{2}a direct normal insolation).

Photovoltaics

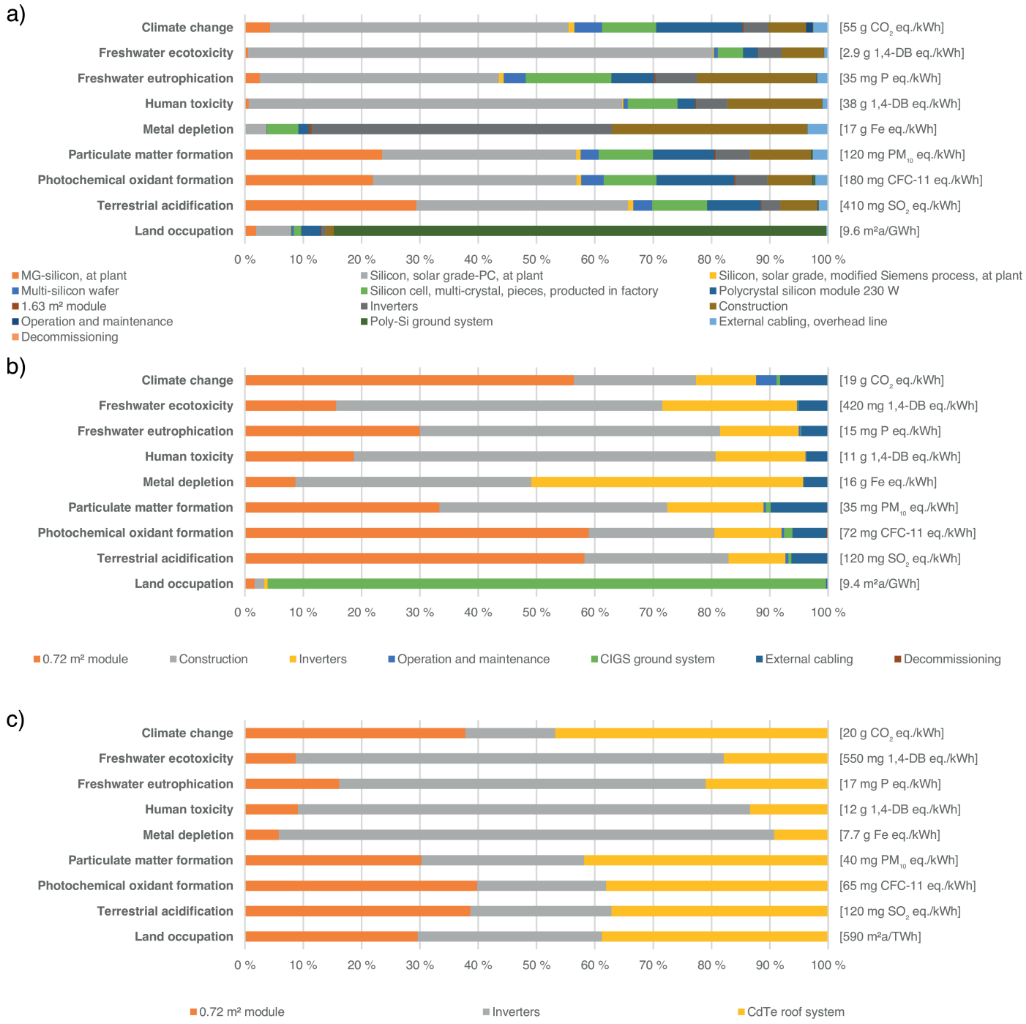

Figure S6: Contributions of different components and life cycle stages to the life cycle impact of three photovoltaic power systems: a) polycrystalline silicon roof mounted, b) copper-indium-gallium-selenide (CIGS) ground-mounted, and c) cadmium-telluride (CdTe) roof-mounted. The solar cells are assumed to be manufactured in China (Si) and the United States (CIGS, CdTe). Results are for US operation under optimal conditions (2400 kWh/m^{2}a).

Nuclear power

Figure S7: Contribution analysis of nuclear power plants: a) boiled and b) pressurized water reactor power plants in the US and Europe, respectively.

Geothermal power

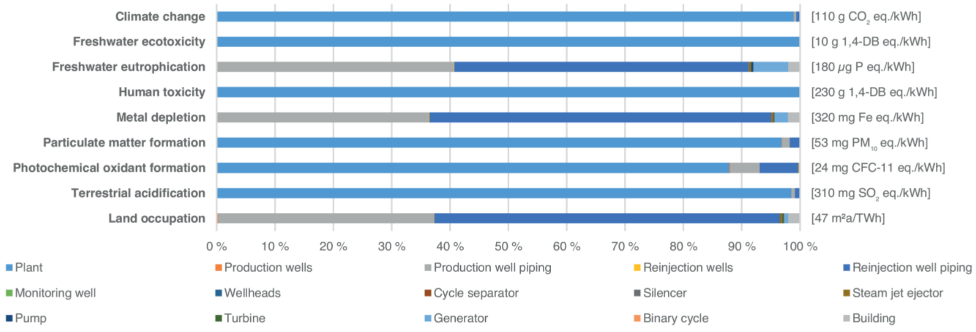

Figure S8: Contributions of different components and life cycle stages to the life cycle impact of a geothermal (binary flash) power plant in the OECD Pacific region.

Biopower

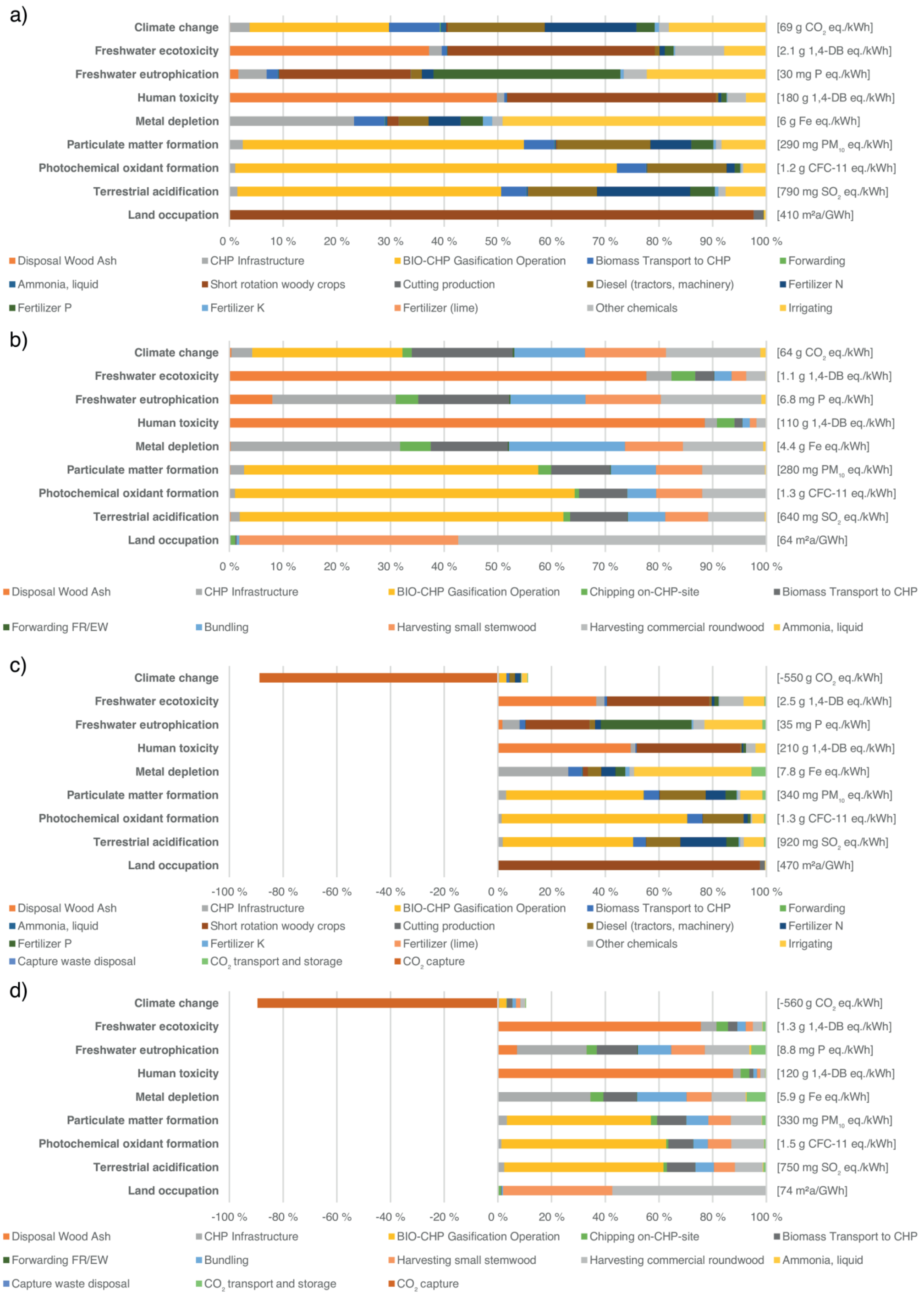

Figure S9: Contributions of different components and life cycle stages to the life cycle impact of four biopower systems: a) and c) short rotation wooden coppice (SRWC, without and with CCS), and b) and d) forest residues (without and with CCS). Global assumptions.

Life cycle inventories

Life cycle inventories for solar technologies (photovoltaics and concentrating solar power), hydropower, wind power, natural gas, coal power, are all adapted from Hertwich et al. (2015)[1]. Both nuclear power inventories are adapted from ecoinvent 2.2[2]. The basis for the biomass inventories is Singh et al. (2014). We utilize inventories of diesel, fertilizer, chemical and irrigation inputs to woody bioenergy crops, as well as land use and direct field emissions of CO2, pesticides, nitrogen and phosphorus compounds, established by Arvesen, et al. [3]. Here, the basic procedure is as follows [3]: First, establish initial inventories based on survey data for existing bioenergy plantations [4], and other data sources; and then, adapt the inventories to the multi-regional and prospective THEMIS framework using results from the spatially explicit land-use model MAgPIE [5, 6]. In the inventory data used in present study, biomass yield per unit area and year vary across regions and years in accordance with results produced by MAgPIE 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 Singh, et al. [7]. The operation of biomass power plants to produce electricity is also modelled based on data from Singh, Guest, Bright and Strømman [7]. Across all regions and years, we assume biomass is supplied by a fifty-fifty split between woody crops and forest residue, as in Arvesen, Luderer, Pehl, Strømman and Hertwich [3].

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