

Editorial

Life Cycle Assessment (LCA) of Environmental and Energy Systems

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1. Introduction

The transition towards renewable energy sources and “green” technologies for energy generation and storage is expected to mitigate the climate emergency in the coming years. However, in many cases, this progress has been hampered by our dependency on critical materials or other resources that are often processed with high environmental burdens. Yet, beyond global warming, several global challenges have to be promptly addressed, including the loss of biodiversity, environmental pollution, water scarcity, and energy security.

Environmental and energy issues are strictly interconnected and require a comprehensive understanding of resource management strategies and their implications. For instance, the depletion and contamination of a vital resource such as water has been related to possible shortages in heat and power generation, distribution and use; on the other hand, water supply requires energy inputs, particularly if the most common sources of natural provision (e.g., groundwater) are not easily accessible. Actions undertaken in separately considered systems may hinder the achievement of optimized benefits and reduction in adverse consequences.

A system perspective is therefore needed to identify and quantify the impact of human activity on the environment. Life cycle assessment (LCA) is among the most inclusive analytical techniques to analyze sustainability benefits and trade-offs resulting from complex systems. This Special Issue presents a collection of original articles, reviews, and case studies focusing on mutual influences of environmental and energy systems. A brief description and discussion of the contributions to this Special Issue is reported hereafter. It is worth noting that the order in which the contributions are presented does not imply any judgment of merit and it is dictated only by narrative purposes.

2. Brief Overview of Contributions to This Special Issue

The selection of macro-economic sectors covered by the articles in this Special Issue is well representative of the main driving applications for energy requirements and greenhouse gas (GHG) emissions, including power generation, bioenergy and biorefinery, building, and transportation.

Renewable energy sources as carriers for electricity generation have attracted quite a lot of attention, particularly photovoltaics. Maranghi and colleagues [1] harmonized the LCA results of several studies in the literature, focusing on 12 different configurations of perovskite solar cell (PSC) technology and identified the main environmental hotspots in PSC technology manufacturing. The development of PSC technology is particularly attractive for photovoltaic energy production thanks to the high photoconversion efficiency. However, the related environmental impacts may vary remarkably depending on technological configurations and materials employed in PSC manufacturing.

In particular, the cradle-to-gate results of this harmonization effort highlight (i) gold used as the back contact, (ii) the conductive solar glass, and (iii) the consumption of organic solvents utilized in the synthesis of the electron transport layer as the materials embedding the highest environmental impacts of PSC manufacturing. The harmonized results provided by these authors constitute a benchmark for PSC technological advancements and they may also orient future efforts towards integrative research between LCA and toxicological assessment tools to better understand and model toxicity implications of perovskite compounds.

Piasecka and colleagues [2] explored the environmental impacts of a 1 MW photovoltaic (PV) power plant by cradle-to-grave LCA with the dual goal of analyzing the state-of-the-art and proposing potential improvements of its overall environmental performance. While Poland was set as the geographical level in which the power plant is located, several life cycle stages (e.g., production and waste management) usually occur in other European countries so that the main results can be considered to be representative of the average situation in this region. Among the analyzed variables, the greatest environmental burdens resulted from the intensive material and energy requirements employed in the manufacture of PV panels and loss through final disposal in landfill. In particular, potential harmful effects on the health and the ecosystem were associated with the presence of metals (e.g., silver, nickel, copper, lead and cadmium) and polymers (e.g., polyamides 6) in PV panels. These effects can be significantly reduced if pro-environmental management strategies, such as ecodesign practices and efficient recovery and recycling of obsolete PV panels, are successfully implemented.

PV waste management will gain relevance proportionally to the amounts of waste that are expected to arise with the phasing-out of old installations in the upcoming years and decades. Herceg and colleagues [3] applied LCA to compare the environmental performance of different recycling processes for PV systems and assess their contribution to the overall environmental footprint of electricity produced by a standard PV system in Germany. The waste management approaches considered in this study include state-of-the-art recycling technology, further improved by supplemental material recovery, and advanced recycling processes discussed in the literature. The results demonstrate that recycling has a significant potential to improve the environmental profile of PV electricity, particularly by means of climate change mitigation achievements. Beyond benefiting the environment and resource conservation, the establishment of an appropriate recycling scheme will also positively impact the economic and financial balances of the logistic network.

A general agreement on the progressive reduction of thermal power plants in electricity grid mixes does exist. However, in transition times or when the greening of electricity is lagging behind, carbon capture and sequestration (CCS) technology can be suitable solutions to contrast the climate emergency. In this context, Zakuchova and colleagues [4] compared the environmental burdens of a 250 MW coal power plant in Czech Republic, set as the reference scenario, with a hypothetical improvement of the same plant upon implementation of a CCS technology based on activated carbons (AC). An economic feasibility evaluation of the AC-based CCS system was also included in the analysis. The results show that the implementation of an AC-based CCS system in the targeted coal power plant would determine a sensible reduction in environmental impacts, mainly in terms of GHG emissions, compared to the baseline scenario. The payback period of six years estimated in this study is particularly attractive as well as the envisaged economic implications of using CO₂ as a building block in agriculture or industry sectors. Although CCS appears to be a promising technology for the environment and for the economy of the whole process, context-specific parameters such as quality standards for material inputs, combustion efficiency, and CO₂ purification stages may affect the environmental gains achievable through CCS. Ultimately, the highest impact to the ecosystem is attributable to the raw material (i.e., hard coal) extraction that constitutes the input fuel in both scenarios. According to the authors, CCS may provide a viable option in countries where the transition to renewable energy sources is lagging. Further investigation to avert unpredictable and potentially harmful effects associated with the management of CCS systems is also required.

Raugei and colleagues [5] combined net energy analysis and LCA to explore energy and environmental implications of an aggressive decarbonization scenario of the electricity mix in the United Kingdom to 2050. Energy return on investment (EROI), net-to-gross primary energy ratio, and life cycle impact assessment results are computed for fossil and renewable energy sources, carbon storage and sequestration technologies, energy storage systems, and transmission to the grid. The results show that the aggressive decarbonization scenario can be a very promising pathway to mitigate the climate emergency mainly thanks to a larger share of renewable energy sources in the national grid mix. The marginal contribution of energy storage systems for the EROI and LCA results is particularly comforting under a prospective transition to a central presence of variable renewable energy sources (e.g., wind, tidal, and solar) in the future electricity grid mix. However, some trade-offs may result due to detrimental effects of resource depletion potential and human toxicity potential due to the intensive demand for specialty metals essential to, for instance, PV panels and wind turbines and the spatial distribution of these installations, which requires more (copper) transmission lines. Biogas and biomass feedstocks result in low EROI values and they are also responsible for acid emissions, biogas upgrade through scrubbing and membrane filtration may lead to significant improvements in this sense. The planned reduction reliance on biomass as an energy source seems to be supported by these outcomes; however, according to Raugei et al. and colleagues [5], the related debate should include a comprehensive discussion on viable alternatives for organic waste streams.

Four papers addressed, instead, the use of biomass as a raw material for bioenergy and biorefinery purposes. Pergola and colleagues [6] focused on a case study of spatial LCA to identify the most promising locations for the construction of bioenergy power plants in the south of Italy. To this aim, a geographical information system (GIS) was applied to characterize the potential biomass availability in this region as well as to map the proximity to main roads, the existing connection to the electricity grid, the presence of residential areas and of protected areas. (Spatial) LCA was then combined to assess the environmental impacts associated with the loading and transport of harvesting biomass residues from local forest management plans. The use of fossil fuels and the release of pollutant emissions from tire abrasion were detected as the main causes of impacts to the ecosystem and the human health resulting from the movement of logging residues. Based on the spatial LCA results, three sites were selected as the most promising areas, providing essential information for the construction of environmentally preferable options for cogeneration or trigeneration bioenergy plants.

Sharara and colleagues [7] applied LCA to assess the environmental impacts of swine manure management within a thermal gasification scenario that includes drying, syngas production, and biochar field application. Hot-gas efficiency and boiler efficiency were also varied according to alternative models of potential improvements to better understand the implications of thermochemical conversion parameters on the overall environmental performance of the proposed management scenario. The results demonstrate that storage of swine manure liquids contributes for about 60% of the total carbon profile of the investigated system. Manure drying demands energy inputs higher than energy outputs generated from the gasification stage so that innovative drying technologies and the utilization of renewable energy sources may considerably reduce energy requirements and the associated greenhouse gas emissions. Further environmental benefits are achieved through land application of biochar in replacement of traditional fertilizers. In areas where swine manure land application is particularly intensive, thermochemical processing represents a suitable alternative to reduce pressure on the environment and improve the energy performance of common manure management scenarios.

Livestock production and the related manure management systems are highlighted as main contributors to global warming and ecosystem degradation. The development of renewable and low carbon fuel standards has shaped the way in which LCA tools are used to assess a fuel's "greenness," specifically for addressing GHG mitigation. Based on LCA, the United States (US) have defined advanced designation under the Renewable Fuel Standard (RFS2) for biofuels and set a 50% GHG emissions reduction target compared to gasoline. Spatari and colleagues [8] investigated the role of biorefinery co-products in the context of US bioenergy policy goals. More specifically, attributional

and consequential LCAs were applied to assess four alternative winter barley-to-ethanol scenarios and commercial dry-grind technology, in order to meet the advanced designation under the RFS2 for biofuels produced in the proximity of highly populated areas in the mid-Atlantic US. Monte Carlo analysis was applied to estimate confidential levels for stochastic soil and foreground GHG emissions. The results show that co-products are essential to biorefinery economics as well as for meeting the RFS2 designations and the national energy policy goals. Co-products' credits mainly result from avoided fossil-based energy generation employed in traditional scenarios and, even under conservative assumptions, ethanol derived from winter barley would exceed the 50% GHG emissions reduction target set for RFS2 advanced fuels compared to gasoline. In highly populated areas with climate and agronomic conditions comparable to those investigated in this study, biorefinery may constitute a profitable and environmentally preferable solution for advanced biofuels.

Alternative exploitation of agricultural sludges can be aimed at chemical products such as biopolymers. This option was explored by Vogli and colleagues [9], who analyzed the environmental impacts associated with polyhydroxyalkanoate (PHA) production through hybrid thermochemical–biological processes using anaerobically digested sewage sludge as the material input. Five scenarios were developed and compared, of which three scenarios modelled alternative uses of syngas from pyrolysis and biochar gasification, and two scenarios modelled different energy sources for the system. From the energy perspective, the amount of sewage sludge used for onsite energy production, the energy recovery from PHAs at end-of-life, and the fraction of renewables in energy production are the main explanatory variables of the overall energy balance. The outcomes indicate that the selection of the most environmentally sustainable scenario ultimately depends on the priority of regional versus global scale impact effects. The scenario modelling the use of syngas to energy production for the satisfaction of internal electrical and thermal energy requirements is preferable for global scale impact categories such as global warming potential and resource depletion. In contrast, the supply of the total syngas produced for PHA production is preferable for acidification, eutrophication, and similar regional scale effects. In any case, a higher fraction of renewable energy sources can significantly reduce environmental impacts at both the regional and global scale. Further improvements are achievable through the expected technological advancements and the process scale up.

Building and transportation are also major sectors where energy-related advancements (e.g., insulation and battery systems) may play a pivotal role to move modern society towards sustainable production and consumption patterns. Space conditioning is responsible for the majority of carbon dioxide emissions and fossil fuel consumption during a building's life cycle. The environmental impacts resulting from innovative ground-source heat pumps for air conditioning in buildings were explored by Bonamente and Aquino [10]. Based on past work of the same authors, this study compared three scenarios including (i) a conventional ground-source heat pump system (set as the baseline scenario), further upgraded, respectively, with (ii) upstream sensible-heat thermal storage unit (SH-TES), and (iii) upstream latent-heat thermal storage unit containing phase-change materials (PCMs-TES). For all scenarios, two hypotheses were modeled for electrical energy input, namely either it being supplied from the national grid or from PV panels. Enabling the switch from sensible heat storage to latent heat storage, the PCMs-TES system resulted in being the most promising solution for space conditioning compared to other scenarios thanks to the reduction of the volume storage and of electrical energy inputs. These benefits particularly amplify when the enhancement of the overall efficiency performance is pursued along with the exploitation of renewable energy sources for electricity generation.

Materials with thermal storage potential such as, for instance, PCMs, are main means for reducing energy demand in the building sector. To this aim, Di Bari and colleagues [11] coupled LCA and a building simulation to assess the environmental impacts of PCM systems. A new developed software named "Storage LCA Tool" was applied to simulate energy implications at the storage material, component and building levels for a wide set of case studies. The system boundaries are set from

cradle-to-grave and different climate zones are investigated to provide representative results of the European situation for heating, cooling, and ventilation needs. The outcomes demonstrate that PCMs systems are often, but not always, preferable to traditional systems. Environmental impacts are context-specific so the choice of materials, building typologies, insulation levels, and location dictate the ultimate preference for the best solutions. To this aim, the storage LCA tool is highly versatile and informative, and it can be successfully used to conceptualize environmentally preferable solutions for energy efficient buildings.

Hu [12] proposed instead a new metric to describe the embodied environmental performance of buildings. This metric is named life cycle embodied performance (LCEP) and it is defined as the ratio between embodied energy and embodied carbon. LCEP was applied to a training set of buildings in the US. In addition, the results for four environmental impact categories (i.e., acidification potential, eutrophication potential, smog formation potential, and ozone depletion potential) as well as their correlation with LCEP scores were quantified. The results highlight that LCEP is a better indicator for the life-cycle embodied performance of building assemblies and materials than individual embodied energy and embodied carbon metrics. In addition, the environmental impact categories considered in this study are proportional to LCEP and, particularly, ozone depletion potential shows correlation with LCEP results. Exterior building walls and assemblies are the main factor in reducing embodied energy and embodied carbon. LCEP demonstrated to be a suitable indicator of the overall embodied environmental performance of buildings and it can be considered as a novel criterion for designing new buildings oriented to environmental sustainability.

Sustainable and smart mobility as well as associated energy systems are also vital to decarbonize economies and develop a clean, resource efficient, circular, and carbon-neutral future. Bobba and colleagues [13] combined LCA with material flow analysis (MFA) and the EU criticality assessment to provide a systemic overview of strategies to secure the supply of materials and environmental protection associated with mobility batteries in this region. In more detail, the environmental performance of lithium-ions batteries (LIBs) in the EU fleet was explored through a prospective assessment of anthropogenic flows and stock of selected raw materials (i.e., lithium and nickel) in different LIBs chemistries and electric vehicle types (i.e., battery electric vehicles and plug-in electric vehicles) according to different scenarios. The results highlight that the future life-cycle global warming potential of traction LIBs may considerably lessen from an increased share of renewables in the electricity production mix, the adoption of resource efficiency strategies in the manufacturing phase, and improved end-of-life recycling performance. Furthermore, the extension of LIBs' lifetime extension through reuse practices may further enhance the energy storage capacity in the EU, but it might also constrain considerable amounts of lithium and nickel in in-use stock, limiting their availability for approaching material circularity and securing stable material supply in this region.

Kosai and colleagues [14] investigated the transport energy intensity (TEI) for different transportation means (i.e., walking, bicycle, conventional automobile, electrical vehicle, hybrid vehicle, fuel-cell vehicle, bus, and electric train) in 38 Japanese cities between 1987–2015. Depending on the annual modal distribution, the relationship between the intracity transport energy intensity and population density has been analyzed, and the diachronic transition in each city visually interpreted. The results show that TEI decreases according to the following order: automobile, bus, train, bicycle, and walking. Material breakdown and manufacturing contribute the most for small-scale transportation options such as bicycles and automobiles, while it is less relevant for buses and trains. The detected negative correlation between population density and intracity TEI has motivated the authors' hypothesis that cities with low population density have mainly relied on automobiles with a consequential increase in TEI. In particular, this aspect has intensified due to a greater share of fossil fuels in the national electricity grid mix after the nuclear accident in Fukushima. In contrast, medium to highly density populated cities have benefitted from the development and consolidation of public transportation systems such as buses and trains. The strategic implications of these results in regional areas have been also discussed by the authors for the improvement of the intracity lifecycle transport energy efficiency.

Lastly, Nwodo and Anumba [15] provided a review of existing exergetic LCA studies and discussed potential improvements for integration between exergy analysis and traditional LCA. Furthermore, 25 peer-reviewed journal articles that focused on the use of exergy and its methodological advancements in LCA were selected over a time frame from 1990 to 2018. The results indicate that exergy analysis is a multi-disciplinary and emerging field, finding its main application on assessing the use of resources. Particularly, both for energetic and non-energetic resources, exergy analysis drives sustainability assessment on thermodynamic properties and parameters, which usually require less subjective choices compared to fate, exposure, and effects models underlying most LCA methods. Nwodo and Anumba also commented on the opportunity of extending traditional boundaries of exergetic LCA to emissions as well, as they ultimately describe an exergy loss to the environment along with the substance release. This measurement would make characterization independent from a reference substance (e.g., carbon dioxide for global warming potential) and it would also enable the combination of the results of different impact categories into a cumulative value thanks to the use of the same unit of exergy. On the other hand, extensive application of exergy analysis to conventional LCA comes through a systematic and comprehensive determination of exergies covering standard thermodynamic conditions, pure state of resources and emissions, and individual emission amounts. These authors expect that an increasing diffusion of systematic integration between exergy analysis and LCA will enable the overcoming of these limitations, and they propose the term exergy-based life cycle assessment (Exe-LCA) as a new field of research to characterize resource depletion and life cycle emissions.

3. Discussion

This Special Issue comprehends 14 research articles and one review, with the scope investigated being mainly representative of the EU or EU countries (10 papers). Other geographical boundaries discussed include the US (three papers), Japan (one paper), and the world (one paper). Overall, the resulting distribution of geographical scopes provides a selective characterization of energy system-related issues in developed countries and, in one case, of the world, but it lacks inclusion of other major economies such as China or developing countries. Ultimately, a joint and global effort to tackle the energy challenge successfully is needed.

All the papers assessed the environmental burdens related to a selected set of impact categories, among which global warming potential is the most common one. Acidification potential, eutrophication potential, toxicity effects, and resource consumption are also frequently considered. Impact assessment methods reflect the articles' geographical scope distribution, with European methods being applied most (e.g., ILCD, CML, ReCiPe, Ecoindicator99). Impact World method, Cumulative Energy Demand, and exergy indicators are also considered. The prevalence of European methods and case studies also results in the reference to Product Environmental Footprint (PEF) guidelines. This aspect attests some effort to increase comparability among the plethora of impact assessment methods through more coherent, exhaustive, and reproducible LCA applications.

Apart two studies that explicitly focus on end-of-life management, the published articles distribute almost evenly between cradle-to-grave and cradle-to-gate approaches, with the latter extending to the operational phase in a couple of works. This aspect demonstrates the preference for adopting overarching and holistic viewpoints to address environmental assessments and problems. A general agreement is also detectable for combining or integrating LCA with complementary tools and methodologies to tackle the sustainability challenges from multiple angles. More in detail, integrative methodologies include GIS [6], MFA and criticality assessment [13], stochastic modelling for spatial emissions [8], material engineering tools [11], and exergy analysis [15]. While attributional LCA is often the preferred methodological baseline approach, several studies have adopted consequential LCA settings or applied scenario analysis to analyze possible future and context-specific implications in the systems investigated.

Overall, a general agreement clearly emerges on the positive effect of (i) decarbonization of energy sources, and (ii) improvement of process efficiencies through technological progress as key strategies to future environmental sustainability. However, while these strategies are certainly embraceable and overarching at the global level, context-specific analyses are fundamental to capture the inherent variability of local and regional parameters, which ultimately influence the choice of the most preferable alternative to select. The set of case studies addressed in this Special Issue covers a wide range of topics and technologies and provides an insightful perspective on the current research needs. However, it is not comprehensive nor exhaustive and certainly calls for complementary research studies to approach achieving environmental sustainability in energy systems. To this end, alone or in combination with integrative methodologies, LCA can be of pivotal importance and constitute the scientific foundation on which a full system understanding can be reached.

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