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Life Cycle Impact Assessment - A Review of Tools for Sustainable Energy Management

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Abstract: Life Cycle Assessment (LCA) has become an important tool for evaluating the environmental impacts of energy systems, in the context of sustainable energy management. This paper provides a review of LCA software tools, including OpenLCA, SimaPro, GaBi, Umberto, Brightway2, and OpenEco, with a focus on applications in renewable energy systems. The comparison of these tools in terms of their functionalities, data handling capacities, and impact assessment methodologies, provides the results of how suitable they are for different energy systems and industrial applications. Particular attention is given to the interpretation and reporting of LCA results, bearing in mind the challenges associated with uncertainty, sensitivity analysis, and trade-offs in energy systems. The paper also includes a discussion on how LCA tools contribute to environmental protection measures, energy efficiency improvements, and socio-economic considerations in energy policies. The implications for policymakers and industries are also given, with recommendations for improving LCA practices in future energy projects. This review offers practical data for stakeholders in order to optimize energy systems and provide a sustainable and low-carbon future.

Keywords: Life Cycle Assessment, Life Cycle Impact Assessment, Sustainable management, Energy management, Circular economy.

1. Introduction

LCA has become an important and needed tool in the sustainable management of energy systems due to the increasing global emphasis on environmental preservation, decarbonization, and the need for a low-carbon economy. The concept of sustainability in energy management is linked to minimizing environmental impacts through the lifecycle of energy production, distribution, and consumption. LCA is therefore needed, providing a systematic framework to assess the environmental consequences of energy systems, beginning with raw material extraction and ending with waste management [1,2]. This rising trend of LCA application in sustainable energy management can be connected to global problems. One of the most important drivers is the need to meet carbon reduction targets, such as those outlined in the Paris Agreement, which aims to limit global warming to below 2°C compared to pre-industrial levels [3]. The energy sector, which accounts for over 70% of global greenhouse gas emissions, is under significant pressure to decarbonize. LCA has been identified as a methodology to evaluate and assess the environmental footprints of various energy technologies, such as solar, wind, hydropower, and bioenergy, in comparison to conventional fossil-fuel-based systems. Research indicates that renewable energy systems, when assessed through LCA, generally exhibit lower GHG emissions over their lifecycle than fossil fuels, but significant differences exist depending on geographic location, production methods, and supply chains [4-7].

In addition to gas emissions, LCA helps quantify other environmental impacts, including resource consumption, water consumption, air pollution, and land use. For example, LCA studies have demonstrated that while PV energy significantly reduces carbon emissions, it also has relatively high material intensity, including the consumption of rare earth elements [8]. This material demand has implications for resource sustainability, making LCA an important approach to understanding the broader impacts of renewable energy systems. LCA has been used to assess the water consumption associated with energy production, highlighting, for instance, the high water intensity of bioenergy production compared to wind or solar power [9]. Such data just highlights the importance of LCA in environmental impact assessments, guiding policy and investment decisions toward the most sustainable energy options. The growing importance of LCA is also connected with its ability to evaluate trade-offs and co-benefits between different environmental factors. Energy systems are complex, and improvements in one area may lead to unintended consequences in another. However, LCAs have identified potential impacts on biodiversity, especially concerning bird and bat populations [10]. These findings show how LCA provides a holistic view, considering not only direct emissions but also secondary and tertiary environmental effects. This makes LCA an important tool for policymakers and industries seeking to balance decarbonization goals with broader ecological and social responsibilities.

The integration of LCA into sustainable energy management also aligns with the increasing trend of environmental, social, and governance reporting, where stakeholders, investors, governments, and consumers, demand greater transparency and accountability from energy companies. According to ISO 14040 and 14044 standards, LCA offers a globally recognized framework for measuring environmental impacts, making it a preferred tool for environmental, social, and governance reporting [11]. Companies using LCA to report their environmental performance can provide verifiable data on their sustainability claims. By integrating LCA data, organizations can systematically identify inefficiencies, reduce energy consumption, and lower greenhouse gas emissions, supporting ISO 50001's goal of improving energy performance by an average of 10% over a three-year certification period [12]. This data-driven approach can improve decision-making and foster continuous improvement in line with ISO 50001's energy efficiency targets. However, for LCA to serve as a decision-making tool, the methodologies, tools, and reporting systems must be transparent, and adaptable to the specific needs of energy systems. The complexity of energy systems, the variety of technologies, and the diverse environmental impacts necessitate that LCA methodologies are both flexible and scientifically sound. Various LCIA methodologies, such as ReCiPe, Eco-indicator 99, and ILCD, offer different approaches to impact categorization and normalization, which can lead to varied results depending on the method chosen [13,14]. This variability makes it important to standardize LCA methodologies in the context of energy systems to ensure consistency and comparability across studies.

In recent years especially, the availability of LCA software tools has provided the adoption of LCA in energy management at a higher level. OpenLCA, SimaPro, and GaBi are among the most used software platforms, offering detailed databases and impact assessment methods for environmental analysis [15,16]. OpenLCA, in particular, has gained prominence due to its open-source availability, making it accessible to a broader range of users. Studies have shown that OpenLCA provides capabilities for conducting detailed lifecycle inventories and impact assessments, especially in the context of renewable energy projects [17]. The accuracy and reliability of LCA outcomes are dependent on the quality of data and assumptions used in the analysis. Energy systems often involve complex supply chains and operational conditions, and inaccuracies in lifecycle inventories can lead to unreliable results, potentially undermining the effectiveness of LCA as a decision-making tool. LCA reporting must be clear, transparent, and adaptable to different stakeholder needs. The interpretation of LCA results is often a challenging task due to the complexity of impact categories, the interrelationships between environmental factors, and the inherent uncertainty in lifecycle data. A study by Laurent et al. [18] highlights the difficulties in making LCA results understandable to non-experts, such as policymakers, who may not have the technical expertise to interpret detailed environmental data. This underscores the need for developing standardized reporting formats that simplify LCA findings without compromising scientific rigor. Clear reporting helps ensure that LCA findings can be effectively integrated into energy policy frameworks, guiding the transition to more sustainable energy systems.

This paper aims to conduct a critical review of available LCA tools, with a focus on OpenLCA, in the context of energy management and environmental protection. Then, the paper has the aim to highlight the aspects of LCIA methodologies, interpretation, and reporting in energy and environmental contexts. LCIA represents a phase in LCA where environmental impacts are evaluated across various categories, such as global warming potential, resource consumption, and water usage. This study will examine the applicability and limitations of these methodologies when applied to energy systems. For instance, while ReCiPe provides a detailed analysis of environmental categories, it can sometimes underrepresent the socio-economic implications of energy systems, which is increasingly relevant in policy contexts.

2. Life Cycle Assessment methodologies

LCA represents a structured framework, composed of four key phases: (1) goal and scope definition, (2) life cycle inventory (LCI) analysis, (3) life cycle impact assessment (LCIA), and (4) life cycle interpretation (Fig.1). Each phase plays a crucial role in ensuring the accuracy and reliability of the environmental assessment [19,20]. The ISO has formalized this framework in the ISO 14040 and ISO 14044 standards, which provide guidelines for conducting LCAs in a consistent and transparent manner [11]. Goal and scope definition, as the first phase represents the basis of any LCA. It involves clearly defining the purpose of the study, the system boundaries, and the functional unit. The functional unit represents the core element as it quantifies the function of the product or system under assessment, ensuring that comparisons between different systems are meaningful. In an LCA of energy systems, the functional unit might generate 1 MWh of electricity, allowing a fair comparison of the environmental impacts of different energy technologies such as coal, wind, and solar [21]. Defining system boundaries is equally important because it determines what processes and life cycle stages will be included in the assessment. This can range from the beginning to the end of the lifecycle analysis, which covers the entire cycle from raw material extraction to disposal. The scope definition should also outline the environmental impacts that will be assessed, such as global warming potential, water consumption, resource consumption, or human toxicity. Research has shown that unclear or inconsistent goal and scope definitions can lead to different LCA results, even when assessing similar systems, highlighting the importance of precision in this phase [19].

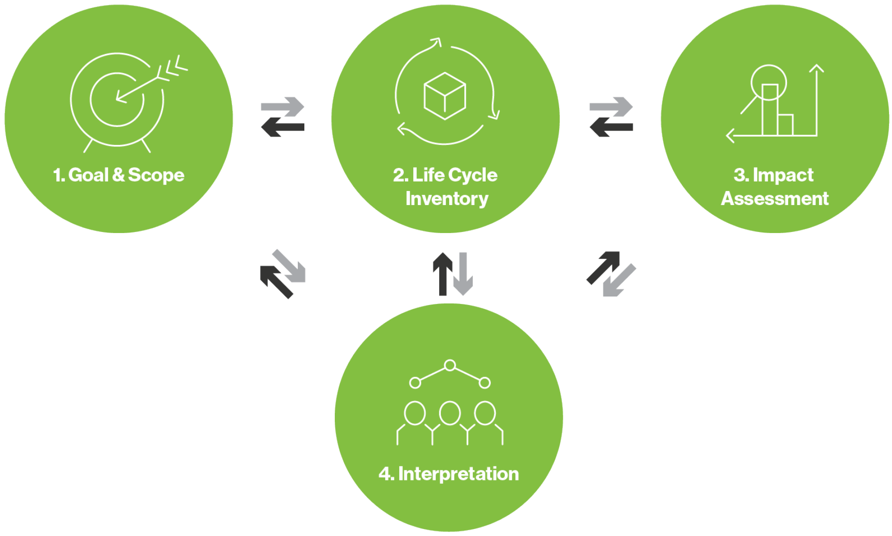

Figure 1. The four key steps of LCA [22]

Inventory analysis is the second phase of LCA and involves the collection and quantification of data on all inputs and outputs associated with the system being studied. This includes raw material inputs, energy use, emissions to air, water, and soil, and waste generation across all life cycle stages, from raw material extraction to end-of-life disposal. The accuracy of the LCI phase is heavily dependent on the quality of the data used, which can be a significant challenge. Data can come from a variety of sources, including industrial databases such as Ecoinvent, Agri-footprint, or ELCD, as well as site-specific measurements or academic literature [23]. The use of generic data from databases, while convenient, may not fully capture the specificities of a system or geographic region, leading to uncertainty in the results. The carbon footprint of renewable energy technologies can vary significantly depending on location-specific factors such as solar insolation for PV systems or wind patterns for wind turbines [24]. The complexity of modern supply chains also makes inventory analysis a difficult task. Many energy systems rely on materials sourced from multiple countries, each with different environmental regulations and practices. This makes data collection and management an important aspect of the inventory phase. The LCIA phase translates the data from the inventory analysis into potential environmental impacts. This is done using a set of predefined impact categories, such as global warming potential, eutrophication, acidification, and ozone depletion. These impact categories are selected based on the goals and scope defined in the first phase and are calculated using established LCIA methodologies, such as ReCiPe, Eco-indicator 99, ILCD, and TRACI [25]. For instance, ReCiPe represents often used method that includes environmental impacts into a single score, making it easier to interpret complex results [26]. However, each LCIA method has its strengths and limitations. ReCiPe focuses on environmental impacts and may not adequately capture the socio-economic aspects of sustainability, which are increasingly important in energy systems [27]. The choice of impact assessment method can influence the outcomes of the LCA, as different methods may prioritize different environmental indicators. The study found that using ILCD versus ReCiPe to assess the ecological impact of wind energy led to different conclusions regarding its material use and overall sustainability [28]. As such, the LCIA phase requires detailed consideration of which methodology best aligns with the objectives of the study and the specific characteristics of the system being assessed. The final phase, life cycle interpretation, includes evaluating the results from the previous phases to draw meaningful conclusions and provide recommendations. The interpretation phase is important for identifying the most significant environmental impacts and determining areas for improvement within the system being assessed. Interpretation also includes uncertainty analysis, sensitivity analysis, and scenario analysis to evaluate the robustness of the results. The uncertainty analysis can quantify how variations in input data (such as energy consumption or emissions) affect the final results, which is crucial in complex energy systems where data may be uncertain or incomplete [29]. Sensitivity analysis, on the other hand, helps identify which parameters have the most influence on the LCA results. In an LCA of bioenergy systems, sensitivity analysis might reveal that the type of feedstock used (e.g., corn, switchgrass, or algae) has an impact on the overall greenhouse gas emissions [30]. Scenario analysis allows for the comparison of different alternatives, such as the use of different energy sources or production technologies and is used in LCAs to evaluate the potential environmental benefits of future technological improvements or policy changes. The interpretation phase is also important in communicating LCA results to stakeholders, including policymakers, industry leaders, and the public. Effective interpretation requires not only technical expertise but also an understanding of how to present complex data in a clear and actionable way. Especially in the energy sector, where LCA results are used to inform policy decisions related to decarbonization and renewable energy deployment [18]. Misinterpretation of LCA results can lead to poor decision-making, such as underestimating the environmental impacts of certain technologies or overestimating the benefits of others.

3. LCA methodologies application in energy sectors and industries

It is important to emphasize that LCA is not a novel approach, it emerged in the late 1960s and early 1970s and developed as a tool to assess the resource use and waste generation of industrial processes. The first application of LCA to energy systems occurred in the context of evaluating different power generation technologies and their environmental impacts, particularly in response to the energy crises of the 1970s. During this period, energy efficiency became a focus of both government policies and corporate strategies, leading to the adoption of LCA methodologies to understand the full lifecycle environmental impacts of energy production [31]. In the early stages of its development, LCA methodologies were primarily focused on evaluating the resource and energy inputs of conventional energy systems, such as coal and oil-based power plants. These initial assessments were relatively simple, focusing on direct emissions and fuel consumption, and did not consider the broader environmental impacts, such as land use or biodiversity loss. The focus was mainly on improving energy efficiency, which was seen as a critical strategy to reduce dependency on fossil fuels. For instance, early LCAs on coal-fired power plants primarily assessed fuel consumption and CO2 emissions, providing insights into how efficiency improvements in plant design lower emissions could and reduce resource use [32]. However, these early assessments were limited in scope, as they did not fully account for the environmental burdens associated with upstream processes, such as mining and transportation, or downstream impacts, such as waste disposal and decommissioning. As environmental awareness grew during the 1980s and 1990s, particularly following the publication of the Brundtland Report in 1987, which introduced the concept of sustainable development, LCA methodologies began to expand in scope. Researchers recognized that energy systems needed to be assessed not only in terms of their direct energy use but also in terms of their full environmental impacts, including resource depletion, pollution, and ecosystem degradation. This led to the development of more comprehensive LCA frameworks that included impact categories such as global warming potential, acidification, and eutrophication. During this period, the first standardized LCA methodologies were introduced, with the publication of the ISO 14040 and ISO 14044 standards in the late 1990s [33]. These standards provided a consistent framework for conducting LCAs, allowing for better comparability between studies and the inclusion of a broader range of environmental impacts. The application of LCA to renewable energy systems gained momentum in the 1990s as renewable technologies such as wind, solar, and hydropower began to scale up. As these technologies were viewed as more sustainable alternatives to fossil fuels, researchers sought to assess their environmental benefits using LCA. Early LCAs on wind energy, for example, focused on the energy payback time, and how long a wind turbine needed to operate to produce the same amount of energy required for its manufacture and installation [34]. These studies showed that wind energy had a lower environmental impact compared to coal and natural gas, with shorter energy payback times and lower greenhouse gas emissions. However, as renewable energy technologies grew in complexity and scale, the need for more sophisticated LCA methodologies became apparent. Issues such as land use, material scarcity (e.g., rare earth metals for wind turbines), and end-of-life disposal started to gain attention, leading to more detailed LCAs that considered these additional factors [35]. The 2000s marked a shift in the application of LCA to energy systems, as the focus expanded from energy efficiency to decarbonization and climate change mitigation. The growing recognition of climate change as a global challenge prompted a surge in LCAs that specifically focused on the carbon footprint of energy systems. Studies increasingly compare the global warming potential of various energy technologies, with an emphasis on renewable energy sources like solar, wind, and bioenergy. LCAs of PV systems demonstrated that while solar power produces very low emissions during operation, the manufacturing process for PV panels, especially the extraction and processing of silicon, contributed to their overall environmental impact [36]. This highlighted the need for improvements not only in energy generation technologies but also in the production processes that support them. Bioenergy also became a focus of LCA in the 2000s, particularly in the context of biofuels. The introduction of biofuels as an alternative to fossil fuels led to a wave of LCA studies assessing their environmental benefits and drawbacks. Initial assessments were optimistic, showing that biofuels, particularly ethanol and biodiesel, could significantly reduce greenhouse gas emissions compared to gasoline and diesel [37]. However, subsequent studies revealed a complex picture, showing that the full lifecycle impacts of biofuels, particularly in terms of land use change, water consumption, and biodiversity loss, were not always as favorable as initially thought. LCAs of bioenergy systems, for example, revealed that large-scale biofuel production could lead to deforestation, soil degradation, and increased food prices, raising concerns about the sustainability of biofuels [38]. These findings showed a reevaluation of bioenergy policies and led to more detailed LCA methodologies that could better capture the trade-offs associated with biofuel production. In recent years, LCA methodologies have continued to evolve in response to the growing complexity of energy systems and the increasing emphasis on sustainability. The rise of integrated energy systems, which combine multiple renewable technologies with energy storage and grid management solutions, has prompted the development of more dynamic and flexible LCA approaches. Modern LCAs of integrated energy systems assess not only the environmental impacts of individual technologies but also the synergies and trade-offs between them. The LCAs of hybrid renewable systems, such as wind-solar installations with battery storage, evaluate how these systems can reduce greenhouse gas emissions and improve energy reliability while minimizing resource use and land occupation [17]. But it should be mentioned that recent findings in LCA methodologies have placed greater emphasis on incorporating socio-economic and technological factors into the assessment of energy systems. The development of dynamic LCA models, which can simulate changes in energy systems over time, has allowed researchers to assess how technological advancements, policy interventions, and market trends may influence the environmental performance of energy systems in the future. Dynamic LCAs of energy systems, for example, can model how improvements in battery storage technology or advancements in carbon capture and storage could reduce the overall environmental impacts of renewable energy systems [24]. The overview of the application of LCA methodologies in various energy sectors and industries is given in Table 1, including solar energy, wind energy, bioenergy, hydropower, nuclear energy, oil and gas, and energy storage systems.

Table 1. LCA methodologies application in energy sectors and industries

Energy sector/ Industry	LCA methodology	Description	Findings	References
Solar Energy	ReCiPe, ILCD	LCA for solar energy often focuses on the production and end-of-life disposal of photovoltaic panels. Studies show low operational emissions but higher impacts during manufacturing.	Solar power has low lifecycle emissions but high impacts during panel manufacturing and disposal.	[24, 36]
Wind Energy	ReCiPe, Eco-indicator 99	LCAs on wind energy reveal that operational emissions are minimal, with material use (e.g., rare earth metals) and land use being significant factors.	Wind energy has low emissions during operation, but material use and land occupation are critical environmental concerns.	[28, 34]
Bioenergy	ReCiPe, CML	Bioenergy LCAs assess the lifecycle from feedstock cultivation to energy production, showing significant variability in	Bioenergy's sustainability is highly dependent on feedstock and land use; certain biofuels may have	[37, 38]

		emissions depending on the feedstock type and land use.	negative impacts on biodiversity.	
Hydropower	ILCD, Eco-indicator	Hydropower LCAs focus on land use, ecosystem disruption, and sedimentation, with minimal operational emissions but large-scale environmental impacts during dam construction.	Hydropower is generally considered a low-emission energy source, but it causes significant ecological disruption and land use.	[39, 40]
Nuclear Energy	ReCiPe, ILCD	Nuclear energy LCAs primarily focus on uranium mining, plant construction, and waste management. Operational emissions are low, but long-term waste disposal presents challenges.	Nuclear power has a low carbon footprint but faces issues with long-term waste disposal and the environmental impacts of uranium mining.	[41,42]
Oil and Gas	CML, TRACI	Oil and gas LCAs often assess upstream emissions during extraction and refining, with a focus on greenhouse gases, acidification, and water consumption.	Oil and gas are high in lifecycle emissions, with significant greenhouse gas output during extraction and refining.	[8,43]
Energy Storage Systems	ReCiPe, ILCD	Energy storage systems, particularly batteries, are assessed using LCA for their entire lifecycle, with high environmental impacts noted during material extraction and disposal.	Batteries used in energy storage systems have high environmental impacts during raw material extraction and end-of-life disposal.	[24,44]

4. Review of LCA software tools

The most widely used LCA tools, OpenLCA, SimaPro, GaBi, Umberto, Brightway2, and OpenEco, offer a range of functionalities that facilitate the collection, modeling, and interpretation of lifecycle data. These tools enable the evaluation of the environmental impacts of products and processes across their full lifecycle, from raw material extraction to end-of-life disposal. Each software has distinct strengths and limitations, particularly in the context of sustainable energy management, where the complexity and scale of systems can vary significantly. OpenLCA is an open-source LCA software that has gained attention due to its accessibility and flexibility [16]. One of its major advantages is its open-source nature, allowing users to freely access and customize the software according to specific project needs. OpenLCA supports a range of lifecycle databases, including Ecoinvent, Agribalyse, and the European Life Cycle Database. Its modular structure also allows for the integration of new methods and impact categories, which is useful for assessing renewable energy technologies, such as wind and solar power, where specific environmental impacts, like rare earth material usage, need to be tracked. OpenLCA's ability to handle large datasets and complex supply chains makes it ideal for detailed studies of renewable energy systems. In PV system assessments, OpenLCA can model the entire lifecycle, from silicon extraction to panel disposal, and calculate the global warming potential and energy payback time with high precision [36]. On the other hand, while it offers customization options, its user interface can be challenging for those without a strong technical background, requiring more knowledge to navigate the tool. Additionally, its reliance on external databases means that the quality of results is dependent on the accuracy and completeness of the input data. This can be a concern in regions where specific lifecycle data for renewable technologies are limited, potentially affecting the robustness of the assessments.

SimaPro, developed by PRé Sustainability, is another LCA tool that is often considered the industry standard for lifecycle assessments. SimaPro represents proprietary software, meaning users need to purchase a license, which can be costly for smaller organizations or academic institutions. However, SimaPro's strength lies in its functionality and ease of use. It offers an intuitive user interface, making it accessible to users with varying levels of expertise. SimaPro supports many impact assessment methods, including ReCiPe, CML, and TRACI, which are used for analyzing energy systems. Its ability to handle multi-scenario comparisons for studies that assess multiple energy sources, such as wind, solar, and nuclear power, allows it to evaluate trade-offs between different environmental impacts [26]. SimaPro is designed for large-scale industrial applications, where detailed product lifecycle data and environmental performance tracking are required. In the wind energy sector, SimaPro has been used to model the environmental impacts of turbine manufacturing, installation, operation, and decommissioning. The software's comprehensive database and scenario modeling capabilities allow for a detailed comparison of different turbine designs, materials, and geographic locations, providing insights into energy efficiency and material optimization [34]. One limitation of SimaPro, is its reliance on proprietary databases, which may limit access to the latest lifecycle data for certain emerging energy technologies. Also. the cost of licensing can be a barrier for smaller entities who may seek more affordable or open-source alternatives.

GaBi, developed by Thinkstep (part of Sphera), is LCA software used extensively in both academic and industrial applications. GaBi is known for its strong focus on industrial applications, particularly in sectors such as automotive, electronics, and energy. GaBi's strength lies in its extensive database, which includes regional-specific lifecycle inventories, for assessments in global supply chains. For energy systems it is used because they rely on international supply chains, such as solar PV and wind turbines, where material sourcing and transportation have the overall environmental impact [24]. GaBi supports a range of impact assessment methods, including ILCD and ReCiPe, to allow users to model the environmental impacts of different energy technologies with high precision. One of GaBi's advantages is its industrial focus with a focus on companies seeking to integrate LCA into product development and sustainability strategies. GaBi has been used in the oil and gas sector to assess the environmental impacts of upstream operations, such as extraction, refining, and transportation. The software's ability to handle complex supply chains shows its good results in identifying opportunities for reducing greenhouse gas emissions and improving resource efficiency in these energy-intensive industries. But, GaBi is a proprietary tool, requiring users to purchase a license, which can be a significant investment for smaller companies and GaBi's user interface may require a higher level of expertise compared to other tools.

Umberto is a proprietary LCA tool developed by Ifu Hamburg, designed with a focus on industrial applications. It is used for modeling material and energy flows within complex industrial systems, used by companies seeking to optimize their production processes and reduce environmental impacts. Umberto's advantage lies in its process modeling. It also allows for the integration of economic and environmental data, for analyzing the financial costs and environmental benefits of process improvements [45]. In the energy sector, Umberto has been applied to assess energy efficiency in manufacturing systems, evaluate the environmental impacts of renewable energy technologies, and model the integration of energy storage solutions in industrial networks. Umberto can model the lifecycle of wind turbine manufacturing, from raw material extraction to the decommissioning phase, allowing users to assess not only environmental impacts such as greenhouse gas emissions but also economic trade-offs related to material use and energy consumption [46]. A limitation of Umberto is that it may not offer the same level of flexibility for purely academic LCA studies that require more customization in impact assessment categories.

Brightway2 is an open-source LCA software designed for advanced users who need a high level of customization and control over their LCA models. Unlike other tools that provide graphical user interfaces, Brightway2 is a Python-based framework that requires coding knowledge to operate. This makes it highly flexible, allowing users to build and customize their own LCA models, integrate new impact assessment methods, and even develop their own databases. Brightway2 is used for academic research and advanced LCA applications that require new methodological approaches or large-scale data manipulation [47]. It can handle large, complex datasets and perform computationally intensive tasks, such as Monte Carlo simulations for uncertainty analysis and sensitivity testing, important in energy systems where the variability in data, such as renewable energy production or material inputs, can significantly affect LCA results. Brightway2 has been used to model the environmental impacts of hybrid renewable energy systems, including wind-solar-battery configurations, allowing the analysis of how changes in energy production patterns influence overall lifecycle emissions [48]. Brightway2's steep learning curve and reliance on coding make it less accessible to non-technical users, limiting its application in industry settings where ease of use is a priority.

OpenEco represents an open-source LCA tool developed as part of collaborative efforts to promote open-access tools, OpenEco is designed for energy systems assessments and integrates environmental databases such as Ecoinvent and the ELCD, allowing to have lifecycle analyses with pre-configured templates and impact categories customized to renewable energy systems, such as solar and wind power [49]. It is used often for smaller-scale LCA projects or in order to conduct rapid assessments of their environmental impacts. In energy systems, OpenEco has been applied to assess the lifecycle impacts of PV installations, focusing on greenhouse gas emissions, material intensity, and land use. The simplified approach offered by OpenEco allows the identification of hotspots in energy systems and to development of strategies to mitigate environmental impacts, and it can be used for initial sustainability assessments [50]. Its limitations in handling more complex datasets and its relatively simplified methodology compared to other LCA tools like SimaPro and GaBi make it less suitable for detailed industrial applications or research requiring high levels of precision.

In order to have a clear overview of the analyzed LCA tools a comparative table (Table 2) is given. The table shows features such as license type, accessibility, main focus, user interface, data libraries, integration with energy systems, impact assessment methods, and other criteria. It can be useful in selecting the appropriate tool based on project requirements, complexity, and user expertise.

Table 2. Comparative table of LCA tools

LCA tool	License	Access	Focus	User interface	Data libraries	Integration with energy systems	Impact assessment methods	Ref
OpenLCA	Open Source	Free	General LCA, customizable for various sectors	Moderate, requires technical expertise	Ecoinvent, Agribalyse, ELCD	Highly suitable for energy systems, including renewables	ReCiPe, ILCD, CML	[23,36]
SimaPro	Proprietary	Paid	Comprehensive LCA, industrial and academic applications	User-friendly, easy to navigate	Ecoinvent, Agri-footprint, Industry-specific databases	Suitable for detailed industrial and energy systems comparisons	ReCiPe, CML, TRACI	[26,34]
GaBi	Proprietary	Paid	Industry-focused LCA, particularly in energy-intensive sectors	Highly User-friendly, suitable for industrial use	Ecoinvent, GaBi proprietary databases	Optimized for industrial energy systems, especially for large-scale operations	ReCiPe, ILCD, CML	[19,24,28]
Umberto	Proprietary	Paid	Material and energy flow modeling in industrial systems	Graphical, drag-and-drop interface	Ecoinvent, Industry-specific databases	Effective for industrial energy systems and process optimization	ReCiPe, ILCD, CML	[45,46]
Brightway 2	Open Source	Free (requires Python knowledge)	Highly customizable LCA modeling, academic research	No GUI, Python-based coding	Custom databases via Python integration	Advanced modelling for energy systems with complex supply chains	Custom methods, full flexibility in assessment	[47,48]
OpenEco	Open Source	Free	Simplified LCA for rapid	User-friendly,	Ecoinvent, ELCD	Simplified assessments for	ReCiPe, ILCD	[49,50]

	sustainability assessments	simplified templates		renewable energy technology

The main focus in this paper analysis is the following comparative table (Table 3), analyzing their use in renewable energy and low-carbon economy projects. In this analysis is presented each tool's strengths, limitations, and main use cases in renewable energy assessments and modeling transitions to low-carbon economies. This comparison provides insights into which tool best fits different project needs, whether for small-scale renewable energy assessments or complex decarbonization analysis.

Table 3. Comparative table of LCA tools for renewable energy and low carbon economy

LCA tool	Use of renewable energy	Low carbon economy uses	Strengths in renewable energy	Strengths in the low carbon economy	Limitations	Ref
OpenLCA	Used for assessing renewable energy systems like wind, solar, and bioenergy. Highly adaptable for decarbonization projects, providing detailed lifecycle inventories for renewable energy technologies and allowing users to model system-wide impacts of energy transitions.	Highly effective for modeling decarbonization pathways in energy systems. OpenLCA's modular design allows users to assess carbon reductions across various scenarios, including renewable energy adoption and improvements in energy efficiency. Used in academic and policy studies for national and regional energy transitions.	Open-source, customizable, and flexible. Supports extensive renewable energy datasets. Used in academic research for evaluating renewable energy adoption and decarbonization pathways.	OpenLCA flexibility and modular structure allow for detailed decarbonization pathway modeling. Frequently used in policy studies to assess energy transition scenarios and carbon reduction impacts.	Requires technical expertise and familiarity with databases like Ecoinvent. Limited for users looking for rapid assessments without significant customization.	[23,36]
SimaPro	Frequently used for renewable energy comparisons, such as evaluating the environmental impact of solar vs. wind power. Also used in policy scenarios for energy transitions and industrial-scale LCAs for energy efficiency improvements.	Frequently used to assess low-carbon technologies and their impacts on reducing greenhouse gas emissions. SimaPro allows multi-scenario comparisons, making it an ideal tool for modelling transitions to low-carbon economies through energy technology improvements.	Comprehensive, with large datasets that support multi-scenario comparisons. Ideal for industry and policy applications where different renewable energy systems need to be compared.	Strong in multi-scenario comparisons, making it an ideal tool for assessing the transition to low-carbon economies. Frequently used by industries and policymakers to model low-carbon technology adoption.	Proprietary, high cost, and less flexible for users who need fully customizable solutions. Typically requires a larger investment to access data for industry-wide analyses.	[26,34]

GaBi	Strong focus on renewable energy in large-scale industrial applications. Used to assess the impacts of energy-intensive processes, such as the production of solar panels and wind turbines, with detailed regional data for supply chains.	Primarily focused on industrial energy systems and the low-carbon economy at a large scale. Its comprehensive databases and advanced scenario modelling make it well-suited for assessing carbon reduction strategies in manufacturing and energy production, particularly in energy-intensive industries.	Extensive regional and industry-specific data. Focuses on renewable energy technologies within large-scale industrial supply chains, making it highly applicable for companies involved in energy production.	Focuses on large-scale, industrial low-carbon strategies. GaBi excels in integrating regional data for detailed lifecycle assessments of industrial energy systems transitioning to a low-carbon economy.	Proprietary and focused heavily on industrial use, making it less accessible for smaller projects or academic studies. High cost limits its use for non-commercial applications.	[19,24,28]
Umberto	Primarily used for industrial applications but can be adapted to model energy efficiency in renewable energy processes. Particularly suited for assessing material flows in renewable energy systems, including energy storage and integration with grid infrastructure.	Mainly used for modelling process efficiency improvements in industrial systems. Umberto is capable of assessing material flows and energy savings in low-carbon production systems, though less commonly applied in macro-level energy transition scenarios.	Excels in process modelling, including energy flows and storage. Can be used to optimize renewable energy systems at an industrial level, especially for integrating renewable energy with existing processes.	Capable of modelling material and energy flows in low-carbon production systems. Best used for process optimization within industries looking to reduce their carbon footprint.	Proprietary and not as adaptable for large-scale energy system decarbonization . Primarily used for industrial applications with limited use in macro-level energy transitions.	[45,46]
Brightway 2	Highly flexible for complex renewable energy systems, including hybrid energy models (e.g., wind-solar-battery systems). Provides extensive customization for researchers focusing on	Ideal for advanced low-carbon economy studies due to its customization. Researchers can model specific decarbonization strategies, such as the integration of renewables with carbon capture	Fully customizable for complex, hybrid renewable energy systems. Ideal for academic research on long-term renewable energy impacts and decarbonization pathways in the	Highly flexible for advanced decarbonization strategies. Ideal for academic and policy studies that require complex, long-term low-carbon economy modelling, particularly in combination	Requires Python coding expertise, making it less accessible for users without a technical background. The steep learning curve, but highly flexible for complex research.	[47,48]

	long-term decarbonization studies and scenario modelling in renewable energy development.	and storage (CCS) or hydrogen fuel cells and assess their long-term impacts on global emissions.	low-carbon economy.	with renewables and CCS technologies.		
OpenEco	Optimized for rapid assessments of renewable energy systems. Often used for small-scale solar and wind energy LCAs with predefined templates, but lacks the capacity for detailed, large-scale modeling of complex energy systems.	Best suited for initial assessments in small-scale low-carbon economy projects. OpenEco can quickly model renewable energy adoption in communities or businesses but lacks the complexity needed for comprehensive national or industry-wide low-carbon transition analyses.	User-friendly and accessible for quick renewable energy assessments. Best suited for small-scale projects or early-stage renewable energy modeling in businesses or communities.	Quickly models small-scale transitions to low-carbon energy solutions. Best used for initial assessments and community-based low-carbon projects, but lacks the depth needed for broader policy or industry-scale applications.	Limited capacity for handling large datasets and complex energy systems. Simplified templates restrict detailed analysis of low-carbon and renewable energy transitions.	[49,50]

5. Discussion

Each analyzed tool provides different features and functionalities, suitable for different applications, from small-scale renewable energy assessments to large-scale industrial decarbonization facilities. One of the most significant challenges in interpreting LCA results is managing uncertainty and variability in the data. Especially for renewable energy systems, where regional variations, supply chain complexities, and operational conditions can significantly influence the outcomes. In solar energy systems, the carbon footprint of PV panels can vary depending on the geographic location of the manufacturing site and the energy mix used during production [8,36]. Sensitivity analysis helps identify the parameters that most influence the results, such as the efficiency of solar panels or the energy intensity of the production process. However, conducting these analyses requires tools like OpenLCA and Brightway2, which offer flexibility for scenario modeling and uncertainty quantification [47,48]. It is important to highlight that LCA is used for assessing the environmental impacts of energy systems and identifying the path towards decarbonization. Tools like SimaPro and GaBi are often used for evaluating the lifecycle emissions of industrial-scale energy projects, helping to quantify the benefits of transitioning from fossil fuels to renewable energy sources [19,24,26,34]. These tools provide detailed insights into the environmental impacts of renewable energy technologies, including their effects on air, water, and soil quality. Wind energy, despite its low operational emissions, can have significant land use impacts, which are often highlighted in LCA studies using GaBi or SimaPro [26]. These are important for policymakers who need to balance the environmental benefits of decarbonization with the potential ecological trade-offs. Energy efficiency improvements are important to reducing the environmental impact of industrial processes and energy systems. LCA tools like OpenLCA and Umberto enable detailed assessments of energy efficiency measures, particularly in sectors such as civil engineering and transportation. It was shown that the use of energy-efficient building materials and transportation technologies can be evaluated in terms of their lifecycle energy use and emissions reductions [7]. Identifying the stages of the lifecycle where energy efficiency gains can be made, LCA can show where to put investments in technology and infrastructure that offer the greatest environmental benefits.

Beyond environmental impacts, LCA is used in understanding the socio-economic effects of energy systems, particularly about local communities and energy policies. The adoption of renewable energy technologies can have significant socio-economic benefits, including job creation, energy access, and improved public health outcomes due to reduced air pollution [24]. LCA tools like Brightway2, which allow for complex modeling of socio-economic variables, are ideal for assessing the broader impacts of energy transitions on communities, particularly in the context of low-carbon policies. ISO standards, ISO 14040 and ISO 14044, provide guidelines for conducting and reporting LCA studies. Tools like SimaPro and GaBi, which integrate ISO-compliant reporting formats, help ensure that LCA findings are communicated clearly and are readily usable by stakeholders in energy systems [23,28].

6. Conclusion

Successful examples of LCA reporting in renewable energy projects include studies on wind energy, where the full lifecycle impacts of turbine manufacturing, installation, and operation have been documented. These case studies, often using tools like GaBi or SimaPro, highlight the environmental benefits of wind energy in terms of reduced greenhouse gas emissions, while also addressing concerns related to land use and biodiversity impacts. Such case studies provide results and best practices for future LCA reporting in energy systems. The findings from LCA studies have significant implications for both energy policy and industrial practices. The results of LCIA can inform decisions on how to prioritize investments in renewable energy, energy efficiency, and pollution control measures. But also LCA findings can guide energy policies by identifying the most effective strategies for reducing carbon emissions and promoting sustainable energy transitions. LCA results from tools like OpenLCA or SimaPro can be used to justify investments in renewable energy technologies, energy efficiency measures, or carbon capture and storage. For industries, LCA offers a roadmap for improving energy efficiency, reducing pollution, and integrating renewable energy into production processes. Tools like Umberto, which focus on material and energy flow modeling, provide insights into how industries can optimize their processes to reduce their environmental footprint/ As energy systems become more complex and decarbonization efforts are even more analyzed, LCA tools should evolve to meet these needs. Future developments in LCA software, such as the integration of AI, will improve the ability of users to process large datasets and conduct more sophisticated analyses.

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