

IMPROVING ENERGY MANAGEMENT EDUCATION THROUGH LIFE CYCLE ASSESSMENT - BRIDGING ACADEMIA AND INDUSTRY

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Abstract: This paper analyses the integration of Life Cycle Assessment (LCA) into energy management education to address global sustainability challenges. It highlights best practices from higher education institutions, emphasizing innovative teaching methods, digital tools, and industry collaboration. The global energy management market is expanding, yet a significant skills gap persists. By incorporating LCA into curricula, students gain important skills to evaluate environmental impacts and design sustainable energy solutions. The paper reviews LCA tools such as SimaPro, OpenLCA, and One Click LCA, demonstrating their relevance in teaching. It also examines how academia-industry partnerships provide practical learning opportunities through internships and case studies. Digital innovations, such as virtual labs and gamification, are shown to improve student engagement. This study shows the importance of bridging academic training with real-world applications, ensuring graduates are prepared for careers in sustainable energy management. The findings support the role of education in achieving global sustainability goals.

Key words: Life Cycle Assessment, energy management education, sustainability, digital tools, academia-industry collaboration, higher education, sustainable energy systems

1. INTRODUCTION

Energy management education is becoming more important than ever for addressing global sustainability challenges. Higher education institutions are responsible for equipping future professionals with the necessary skills. The global energy management systems market is expanding rapidly. In 2020, the industrial sector's market value was approximately \$4.43 billion. Projections indicate that by 2025, the market will reach \$16.3 billion, with a compound annual growth rate of 9.69% from 2025 to 2029 [1,2]. Despite this growth, there is a skills gap in the energy sector. For instance, the UK aims to decarbonize its electricity grid by 2030. However, only 30% of the required workforce for global wind energy projects by 2026 are currently trained. This highlights the urgent need for skilled professionals in the renewable energy industry [3]. Higher education institutions are needed to bridge this skills gap. With the integration of energy management and sustainability into their curricula, they prepare students to meet industry demands. For example, business schools are evolving to address modern challenges by incorporating sustainability, practical learning, and modern technologies into their programs. This approach ensures that graduates are well-equipped to tackle complex issues in the energy sector [4].

The shift to sustainable development has intensified the demand for professionals adept in energy management. A paper [5] highlights that integrating energy management systems, renewable energy, and energy efficiency into academic curricula not only improves the educational experience but also prepares students to deal with global challenges and contribute to sustainable development. The research presented in [6] serves as a case study, showing how universities can address energy efficiency, alternative energy, and carbon management in response to the United Nations' 2030 Agenda for Sustainable Development. Unisa's initiatives have the significant role that HEIs play in promoting sustainable energy practices. Moreover, the University of Alcalá in Madrid has implemented policies that have positioned it as a leading institution in environmentally sustainable practices. These actions not only reduce energy consumption but also serve as educational models for students, highlighting the practical applications of energy management theories [7].

It should be highlighted that LCA represents a systematic method used to evaluate the environmental impacts of a product, process, or service throughout its entire life cycle, from raw

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material extraction to disposal. This approach encompasses stages such as material acquisition, manufacturing, usage, and end-of-life management. With these phases, LCA provides a view of environmental challenges, enabling the identification of stages with significant impacts and opportunities for improvement [8-10]. In the context of sustainable energy management, LCA is needed for assessing the environmental performance of various energy systems. For instance, a study [11] on bioenergy production emphasized the necessity of conducting LCAs that extend beyond greenhouse gas emissions and energy balances. The research highlighted the importance of standardizing assessment methodologies to facilitate meaningful comparisons across different bioenergy systems. Moreover, integrating LCA with economic analyses, such as Life Cycle Costing (LCC), offers a perspective on both environmental and economic aspects of energy systems. A review [12] of existing literature revealed that combining LCA and LCC provides valuable insights into the sustainability and cost-effectiveness of various energy technologies, aiding in informed decision-making. The application of LCA in energy management is not without challenges. A literature review [13] identified key issues, including methodological complexities and the selection of appropriate sustainability indicators. Despite these challenges, the study concluded that LCA remains an important tool for supporting decision-makers in developing more sustainable energy systems. By providing a detailed analysis of environmental impacts across all stages of an energy system's life cycle, LCA informs strategies aimed at reducing negative environmental effects. Its integration with economic assessments improves its utility, supporting informed decision-making in the energy sector. In educational settings, digital tools are employed to teach LCA, improving students' understanding of environmental impacts. SimaPro Craft is widely used in academia for teaching LCA concepts, offering databases and user-friendly interfaces that facilitate learning [14]. OpenLCA is another used tool; as open-source software, it provides flexibility and transparency, making it suitable for both teaching and research purposes [15]. Additionally, One Click LCA offers free educational licenses, enabling students and educators to integrate LCA into building and construction-related projects [16]. These tools collectively support the effective incorporation of LCA into educational curricula, preparing students to assess and mitigate environmental impacts in their future professional roles.

The main objective of this paper is to review and highlight best practices in integrating LCA into energy management education. It aims to explore how LCA can be effectively included in curricula to improve students' understanding of environmental impacts and sustainable practices. The paper focuses on identifying innovative teaching methods, digital tools, and case studies that improve the delivery of LCA concepts to students. A goal is to address the gap between academic training and industry requirements. Many graduates lack the practical skills needed to apply LCA in real-world scenarios. This paper emphasizes the importance of collaborative approaches between academia and industry to bridge this gap. With the involvement of industry partners, students can gain practical experience through internships, project-based learning, and exposure to real-world case studies. Another objective is to promote the use of digital tools and simulations in teaching LCA. These tools make it easier for students to understand complex concepts and apply them in practical settings. This paper aims to strengthen the connection between education and industry, ensuring that students are better prepared for careers in sustainable energy management. It highlights how integrating LCA into education supports a new generation of professionals capable of addressing pressing global sustainability challenges.

2. THEORETICAL FRAMEWORK AND EDUCATIONAL RELEVANCE OF LCA

LCA represents a method for evaluating the environmental impacts of products, processes, or services throughout their entire life cycle, from raw material extraction to disposal. The International Organization for Standardization has established standards, notably ISO 14040 and ISO 14044, which outline the principles and framework for conducting LCAs [17,18]. The LCA process comprises four key phases (Fig.1):

- Goal and scope Definition to establish the purpose, system boundaries, and level of detail for the study.
- Life Cycle Inventory Analysis (LCI) - compiling data on energy and material inputs and environmental releases associated with each stage of the product's life cycle.

- Life Cycle Impact Assessment (LCIA) - evaluating the potential environmental impacts based on the LCI data, considering factors such as resource depletion, human health, and ecological consequences.
- Interpretation to analyse results to draw conclusions and make recommendations for reducing environmental impacts.

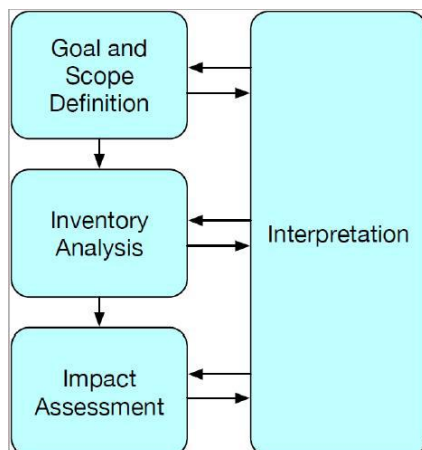


Figure 1 – Phases of LCA [9,17]

In the context of renewable energy, LCA is important for assessing the environmental performance of various energy technologies. For example, a study [19] comparing the life cycle greenhouse gas emissions of different energy sources found that wind and solar power have significantly lower emissions, approximately 10-20 g CO₂ -eq/kWh, compared to coal, which emits around 820 g CO₂ -eq/kWh. LCA is also important in improving circular economy principles by evaluating the environmental benefits of recycling, reuse, and resource efficiency strategies. A review of LCA applications in circular economy contexts highlights its importance in quantifying the environmental performance of circular products and systems, thereby supporting the development of sustainable production and consumption patterns [20]. Furthermore, integrating LCA with circularity indicators can provide a more comprehensive assessment of product sustainability. Research [21] suggests that combining LCA with metrics such as material circularity indicators offers a holistic view of both environmental impacts and resource efficiency, facilitating informed decision-making in product design and policy development.

Integrating LCA into energy management curricula equips students with skills to evaluate environmental impacts comprehensively. By understanding LCA methodologies, students can assess the sustainability of energy systems from production to disposal. For instance, the École Polytechnique Fédérale de Lausanne offers a course titled "Life Cycle Assessment in Energy Systems," which introduces students to LCA principles and their application in evaluating the environmental impacts of energy technologies. Teaching LCA in engineering and environmental programs supports critical thinking and systems analysis skills. Students learn to identify stages in energy systems that contribute significantly to environmental degradation and develop strategies for improvement. A study [22] emphasizes that incorporating LCA into higher education enables graduates to apply sustainability considerations effectively in their professional practices. Moreover, integrating LCA into curricula aligns with the growing industry demand for professionals proficient in sustainability assessments. As industries increasingly adopt sustainable practices, the need for employees skilled in LCA methodologies rises, making such educational integration both timely and essential. Effective collaboration between academia and industry improves the practical relevance of LCA education. The Academia-Industry Collaboration Plan (design model) provides a structured approach to support such partnerships. This model outlines processes and methods to bridge the gap between academic research and industrial application, ensuring that educational outcomes meet industry needs [23]. Real-world case studies are significant in this collaborative framework. With the involvement of industry partners in curriculum development, students gain exposure to current challenges and practical applications of LCA. For example, a study [24] discusses a large-scale industry-academia collaboration in Finland, highlighting how such partnerships provide students with practical experience and improve learning

outcomes. Furthermore, a framework proposed [25] emphasizes the importance of clear communication and mutual objectives in academia-industry partnerships. In the process of establishing common goals and open channels of communication, both parties can effectively contribute to the development of curricula that are both academically rigorous and industrially relevant. The integration of LCA into energy management education, supported by robust academia-industry collaborations, prepares students to meet the evolving demands of the energy sector. Such educational strategies ensure that graduates are not only knowledgeable in theoretical aspects but also adept at applying LCA in real-world scenarios, thereby contributing to sustainable development goals.

3. BEST PRACTICES IN INTEGRATING LCA INTO HIGHER EDUCATION

European Higher Education Institutions have effectively integrated LCA into their energy management curricula, employing innovative teaching methods and digital tools to improve student learning. A study [22] analysed LCA education across various institutions. The research identified 5 distinct LCA learning and competency levels, each differing in study program integration, workload, cognitive domain categories, learning outcomes, and envisioned professional skills. This structured approach ensures that graduates are well-prepared for professional practices in sustainability. In terms of teaching innovations, the University of Liverpool has implemented diverse digital assessment methods to enrich the educational experience. These methods include the use of multimedia creation and interactive platforms, which cater to various learning styles and improve student engagement. Such approaches have been instrumental in delivering complex subjects like LCA more effectively. Furthermore, the integration of energy system models with LCA has been explored to provide students with a holistic understanding of environmental impacts. A study [26] highlights the combination of LCA with energy system optimization models to better represent the energy sector and its dynamics. This integration facilitates improved decision-making processes, offering students practical insights into the complexities of energy systems. Additionally, the adoption of digital tools in teaching has been accelerated by the need for remote learning solutions. Research [27] indicates that educators have discovered new approaches to teaching and have increased their confidence in using digital tools. This shift has led to the development of innovative digital teaching-learning and assessment tools, which have become increasingly important in higher education. Virtual laboratories, interactive simulations, and gamified learning platforms provide immersive experiences that bridge theoretical knowledge with practical application. Virtual labs offer students the opportunity to conduct experiments in a risk-free, cost-effective environment. A meta-analysis examined the impact of virtual laboratories on engineering students' performance. The study analysed 46 studies from 22 publications and found that virtual labs effectively improve learning outcomes by providing hands-on experience without the constraints of physical lab resources. Interactive simulations are also important in education. A study reviewed 31 peer-reviewed empirical studies and revealed that interactive simulations are the most widely used digital tools, accounting for 25 out of 31 studies.

Table 1 – LCA Software comparison for higher education institutions

Software	Features	Use in education	Relevance for teaching
SimaPro	Comprehensive databases, user-friendly interface, scenario analysis, supply chain modeling	Widely used in universities for courses on environmental impact and supply chain analysis	Excellent for hands-on projects, comprehensive but requires licensing costs
OpenLCA	Open-source, customizable, supports multiple impact assessment methods, large database options	Popular for research and teaching due to open access and customization options	Highly accessible for students, supports practical learning through customization
GaBi	Extensive database, advanced modeling capabilities, industry-specific templates	Preferred in industry-focused courses due to real-world applications	Advanced features suitable for capstone projects or applied research
One Click LCA	Focused on construction and building, gamification features, free educational licenses	Used for teaching sustainable construction practices and LCA in architecture	Encourages engagement through gamification, suitable for architecture students
Umberto	Process-based modeling, material flow analysis, integration with ISO standards	Integrated into courses focusing on material flow and industrial ecology	Provides deep insights into material flows, relevant for process engineering

Brightway 2	Python-based, open-source, advanced statistical tools, flexible for research purposes	Ideal for advanced LCA research and teaching programming in sustainability	Best for advanced-level courses, requires prior knowledge of programming
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4. CONCLUSION

Energy management education is important in addressing global sustainability challenges, particularly with the increasing demand for skilled professionals in renewable energy sectors. Higher education institutions have the responsibility to integrate sustainability and energy management into their curricula to prepare students for evolving industry demands. By incorporating LCA into energy management education, students gain comprehensive skills to evaluate energy systems and contribute to sustainable development. The integration of LCA into academic programs aligns with global sustainability goals and industry needs, providing practical and theoretical training for future professionals. Best practices from European universities, such as the structured LCA competency frameworks and digital tools like SimaPro, OpenLCA, and One Click LCA, demonstrate the effectiveness of innovative teaching methods. These tools enable students to engage in practical learning and prepare for real-world challenges in sustainability. Collaboration between academia and industry further improves the relevance of education, offering students exposure to practical applications through internships, case studies, and project-based learning. Digital tools and simulations have revolutionized LCA education by providing interactive and immersive learning environments. Virtual labs and gamification have proven to improve student engagement and comprehension of complex concepts. Real-world applications, such as integrating LCA with energy system optimization models, showcase the importance of bridging theoretical knowledge with practical insights. This paper highlights that integrating LCA into energy management education supports a generation of professionals equipped to tackle pressing environmental challenges.

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