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SUSTAINABILITY ASSESSMENT OF POWER GENERATION TECHNOLOGIES

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Orientadores: Eduardo Gonçalves Serra, DSc.
Ofélia de Queiroz F. Araújo, PhD.

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RESUMO

TOURINHO, T.C.O. **Avaliação de Sustentabilidade de Tecnologias de Geração de Eletricidade.** Tese (Doutorado em Engenharia Ambiental), Programa de Engenharia Ambiental, Escola Politécnica & Escola de Química, Universidade Federal do Rio de Janeiro, 2024. Orientadores: Eduardo Gonçalves Serra, Ofélia de Queiroz Fernandes Araújo

A transição para sistemas energéticos sustentáveis é um desafio global, essencial para mitigar as mudanças climáticas e alcançar os Objetivos de Desenvolvimento Sustentável (ODS) da ONU. O setor de geração de energia desempenha um papel central nesse contexto, devido à sua significativa contribuição para as emissões de gases de efeito estufa e aos impactos sociais e econômicos associados. No entanto, a maioria das avaliações de sustentabilidade concentra-se nas dimensões ambiental e econômica, negligenciando os aspectos sociais. Nesse cenário, este trabalho aborda a integração da dimensão social na avaliação de sustentabilidade de tecnologias de geração de eletricidade, utilizando a Avaliação Social do Ciclo de Vida (ASCV). O objetivo principal é propor metodologias e indicadores que permitam decisões mais holísticas e alinhadas aos ODS, considerando os impactos sociais, técnicos e ambientais. Inicialmente, é realizada uma revisão crítica da aplicação da ASCV no setor elétrico, destacando inconsistências e lacunas em metodologias e indicadores, assim como os principais indicadores utilizados no setor. Em seguida, é proposto um indicador social, o Potencial de Salário Justo Ponderado pelo Emprego, que avalia a justiça salarial e a geração de empregos associadas a diferentes tecnologias de geração de eletricidade, promovendo conexões diretas com diferentes ODS. Por fim, e de forma inovadora, foi desenvolvida uma estrutura de suporte à decisão que integra critérios sociais, técnicos e ambientais, em uma abordagem de ciclo de vida, na escolha de fontes de geração de eletricidade alinhadas a ODS prioritários. A estrutura foi aplicada a estudos de caso envolvendo empresas de diferentes setores. Os resultados demonstram a aplicabilidade do modelo proposto e sua capacidade de orientar escolhas energéticas mais assertivas, reduzindo impactos negativos e promovendo o alinhamento das práticas do setor elétrico aos ODS. Este trabalho fornece uma abordagem para decisões mais conscientes e equilibradas na transição para um futuro energético sustentável.

Palavras-chave: Avaliação social do ciclo de vida; Tecnologias de geração de eletricidade; Objetivos de Desenvolvimento Sustentável; Avaliação do ciclo de vida; Estrutura de suporte à decisão

ABSTRACT

TOURINHO, T.C.O. **Sustainability Assessment of Power Generation Technologies**. DSc. Thesis (Doctorate in Environmental Engineering), Environmental Engineering Program, Escola Politécnica & Escola de Química, Federal University of Rio de Janeiro, 2024. Advisors: Eduardo Gonçalves Serra, Ofélia de Queiroz Fernandes Araújo

The transition to sustainable energy systems is a global challenge, essential for mitigating climate change and achieving the UN Sustainable Development Goals (SDGs). The power sector plays a central role in this context due to its significant contribution to greenhouse gas emissions and the associated social and economic impacts. However, most sustainability assessments focus on environmental and economic dimensions, often neglecting social aspects. In this scenario, this work addresses the integration of the social dimension into the sustainability assessment of electricity generation technologies, utilizing Social Life Cycle Assessment (S-LCA). The main objective is to propose methodologies and indicators that enable more holistic decision-making aligned with the SDGs, considering social, technical, and environmental impacts. Initially, a critical review of the application of S-LCA in the power sector is conducted, highlighting inconsistencies and gaps in methodologies and indicators, as well as the key indicators used in the sector. Subsequently, a social indicator, the Employment-Weighted Fair Wage Potential, is proposed, assessing fair wages and job creation associated with different electricity generation technologies, fostering direct connections to various SDGs. Finally, and innovatively, a decision-support framework was developed, integrating social, technical, and environmental criteria within a life cycle approach for selecting electricity generation sources aligned with prioritized SDGs. The framework was applied to case studies involving companies from different sectors. The results demonstrate the applicability of the proposed model and its capacity to guide more assertive energy choices, reducing negative impacts and promoting the alignment of the power sector's practices with the SDGs. This work provides an approach for more informed and balanced decision-making in the transition toward a sustainable energy future.

Keywords: Social life cycle assessment; Power generation technologies; Sustainable Development Goals; Life cycle assessment; Decision-support framework.

CONTENTS

1. Introduction

Sustainability is more than a concept; it is an urgent necessity to safeguard humanity's survival on Earth. This moment in history to avoid ecosystem collapse is also a profound opportunity for humanity to rediscover its purpose in human and ecological thriving (Dixson-Decleve et al., 2022). The mounting pressure on natural resources, coupled with climate and social challenges, demands immediate and coordinated action. A new dialogue about how society is shaping the future of our planet must include everyone, recognizing that the environmental challenge affects us all and demands universal solidarity (Francis, 2015). In this context, the United Nations' 2030 Agenda emerges as a comprehensive global strategy, calling on governments, businesses, and citizens to unite around the Sustainable Development Goals (SDGs) (United Nations, 2018). These goals represent the global ambition to accelerate sustainable development (Schmidt Tagomori et al., 2024), serving as a transformative framework for reshaping development models, reducing inequalities, and preserving the environmental balance essential for the survival of current and future generations.

The 2030 Agenda and the SDGs have influenced institutions, policies and debates, from global governance to local politics, and while this impact has so far largely been discursive, the goals had some normative and institutional effects as well (Biermann et al., 2022). Achieving the SDGs requires a collective and integrated effort across all sectors of society.

While governments must align public policies with sustainability principles, businesses bear the responsibility of embedding sustainable practices into their operations and strategies, and into the missions and values of organizations, as aligning strategic decisions with global goals amplifies the positive impact of their actions.

One critical area for advancing the SDGs is the energy transition, particularly in the selection of electricity sources. The process of electrification is the foreseen solution for several demands and sectors, and most proposed solutions for the decarbonization of economic sectors entails a tighter connection to the power system either through direct or indirect electrification (Groppi et al., 2025). Therefore, the way energy is generated significantly influences progress toward sustainability. Sustainable electricity consumption, which is about balancing economic growth, social development and environmental protection, is one of the core principles of the SDGs (Mahanta & Talukdar, 2024), thus opting for sustainable electricity is a decision that transcends environmental benefits, fostering social and economic advantages that contribute to the holistic achievement of the goals.

In this scenario, every economic sector, and each company, plays a pivotal role in making conscious energy choices. Integrating the SDGs into their practices paves the way for building a more resilient, equitable, and environmentally harmonious society. Therefore, collective efforts in this direction are not only essential but also urgent to secure a sustainable future for all.

1.1. Sustainable Development Goals

Sustainable development goals (SDGs) represent a universal call to action to end poverty, protect the planet, and ensure that all people enjoy peace and prosperity by 2030. Adopted by all United Nations (UN) Member States in 2015, the 17 SDGs (Table 1.1) are an urgent call for countries to prioritize sustainable development in their policies and actions (United Nations, 2018).

Table 1.1. Sustainable Development Goals and their description (United Nations, 2024)

SDGs	Description
SDG 1: End poverty in all its forms everywhere	The goal is to eradicate extreme poverty for all people everywhere, currently measured as people living on less than $1.25 a day (United Nations, 2024). Despite significant progress, the World Bank highlights that about 8.5% of the world's population still lives in extreme poverty, struggling to fulfill the most basic needs (World Bank, 2024).
SDG 2: Zero Hunger	This goal aims to end hunger, achieve food security and improved nutrition, and promote sustainable agriculture. The Food and Agriculture Organization (FAO) reports that nearly 690 million people are hungry, or 8.9% of the world population, which is an increase of 10 million people in one year and nearly 60 million in five years (World Economic Forum, 2020).
SDG 3: Good Health and Well-Being	Ensuring healthy lives and promoting well-being at all ages is essential, and the SDG #3 key objectives are: Achieve universal health coverage; Reduce maternal mortality; End preventable child deaths; Substantially reduce the number of deaths and illnesses from hazardous chemicals and air, water, and soil pollution, among others (United Nations, 2024).
SDG 4: Quality Education	The goal focuses on inclusive and equitable quality education and promoting lifelong learning opportunities for all. UNESCO reports that about 251 million children and youth are out of school, indicating the importance of more inclusive and accessible education (UNESCO, 2024).
SDG 5: Gender Equality	This goal aims to achieve gender equality and empower all women and girls. UN Women states that gender equality is not only a fundamental human right but a necessary foundation for a peaceful, prosperous, and sustainable world (United Nations, 2024).

SDG 6: Clean Water and Sanitation	Access to clean water and sanitation is a critical aspect of the world's sustainable development. According to WHO, in 2022, globally, at least 1.7 billion people use a drinking water source contaminated with faeces, and 2.2 billion people did not have safely managed services (WHO, 2023).
SDG 7: Affordable and Clean Energy	The International Energy Agency (IEA) highlights the importance of ensuring access to affordable, reliable, sustainable, and modern energy for all, as energy is central to nearly every major challenge and opportunity the world faces today (IEA et al., 2024).
SDG 8: Decent Work and Economic Growth	Promoting inclusive and sustainable economic growth, employment, and decent work for all is crucial. The International Labour Organization (ILO) notes that unemployment and underemployment lie at the core of poverty (UN, 2024).
SDG 9: Industry, Innovation, and Infrastructure	Developing quality, reliable, sustainable, and resilient infrastructure, including regional and transborder infrastructure, to support economic development and human well-being is a key focus.
SDG 10: Reduced Inequalities	The goal aims to reduce inequality within and among countries, which the United Nations describes as a fundamental aspect of achieving sustainable development.
SDG 11: Sustainable Cities and Communities	Making cities and human settlements inclusive, safe, resilient, and sustainable is essential, as highlighted by the United Nations, considering that over half of the world's population lives in urban areas.
SDG 12: Responsible Consumption and Production	The United Nations Environment Programme (UNEP) emphasizes the importance of ensuring sustainable consumption and production patterns, which is crucial for promoting resource and energy efficiency, sustainable infrastructure, and providing access to basic services, green and decent jobs, and a better quality of life for all (UNEP, 2024).
SDG 13: Climate Action	The UN Framework Convention on Climate Change (UNFCCC) underscores the need to take urgent action to combat climate change and its impacts, which is integral to sustainable development (UNCC, 2023).
SDG 14: Life Below Water	Conserving and sustainably using the oceans, seas, and marine resources is vital for sustainable development, as stated by the United Nations.
SDG 15: Life on Land	Protecting, restoring, and promoting sustainable use of terrestrial ecosystems, managing forests sustainably, combating desertification, and halting and reversing land degradation and biodiversity loss are critical, as emphasized by the United Nations.

SDG 16: Peace, Justice, and Strong Institutions	Promoting peaceful and inclusive societies for sustainable development, providing access to justice for all, and building effective, accountable, and inclusive institutions at all levels are crucial goals highlighted by the UN.
SDG 17: Partnerships for the Goals	The United Nations stresses the importance of strengthening the means of implementation and revitalizing the global partnership for sustainable development as key to the success of the SDGs.

Each SDG is interconnected, and often the key to success for one will involve tackling issues more commonly associated with another. The UN has emphasized that achieving these goals requires the partnership of governments, civil society, citizens, and the private sector.

1.2. Power Sector

The power sector is one of the engines of a country's development (Tourinho et al., 2023), and the continuous supply of energy and electricity is a prerequisite for the economic progress of a nation (Rashid & Majed, 2023). Therefore, this sector is also responsible for the pursuit of achieving the SDGs. Power generation technologies can contribute to achieving various SDGs, particularly those related to clean energy, climate action, and sustainable industrial practices. In the context of the ongoing energy transition, the power sector plays a pivotal role in several SDGs (Lassio et al., 2021).

Strielkowski et al. (2021), highlights the growing global demand for electric energy and the necessity for decarbonization through renewable energy sources to address climate change, emphasizing the importance of sustainable development principles in the power sector. It stresses how renewable energy not only addresses environmental issues, but also has significant social impacts, including job creation, improved energy security, and reduced health risks from pollution. Buana et al. (2023), in the same outlook, revolves around the critical role of power system expert engineers in facilitating sustainable energy transitions through active stakeholder engagement and co-creation, underscoring the importance of collaborative efforts among stakeholders to enhance sustainability in the electricity sector. Also, while Martín-Gamboa et al. (2022) emphasize that the energy sector is a driver of social welfare, Pueyo & Maestre (2019) states that access to electricity is a crucial catalyst for economic growth and poverty alleviation in developing nations, propelling economic and social development by boosting productivity and emerging new job-generating enterprises.

The environmental pillar is specially addressed by public policy, e.g., in The Paris Agreement, adopted in 2015 at the UN Climate Change Conference (COP21) (United Nations, 2023a). Also, due to the prevalent use of fossil fuels and the increasing energy demand, electricity is the leading sector in global warming-related emissions (Backes et al., 2021). Therefore, regarding the ongoing energy transition towards low-carbon energy systems, there is a need for reducing reliance on fossil fuels and increasing the use of renewable energy sources to mitigate climate change.

However, although one of the major objectives of energy development is to transition to a low-carbon and secure energy system (Y. Zhang et al., 2021), decarbonization of the power sector can lead to tradeoffs that vary according to the chosen technology (Luderer et al., 2019). Boa Morte et al. (2023), for example, suggest that the energy transition has been driven by SDG#7 (Affordable and Clean Energy) and SDG#13 (Climate Action) while neglecting to assess collateral effects (synergic or antagonistic) on the remaining SDGs. Higher costs associated with commissioning renewable energy systems could hinder economic growth, impacting other SDGs like #1 (No poverty), #2 (Zero hunger), #3 (Good health and well-being), #8 (Decent work and economic growth), #9 (Industry, innovation and infrastructure), and #11 (Sustainable cities and communities). Also, the need to balance conflicting geopolitical interests in addressing climate change must be emphasized (Araújo et al., 2024).

Thus, decisions in the power sector can impact various sustainability dimensions and SDGs, highlighting the complexity of making balanced energy choices. Explicitly and effectively incorporating the SDG framework into the energy sector is a substantial challenge in targeting efficient and sustainable production systems (Martín-Gamboa et al., 2020).

1.3. Life Cycle Assessment

Life Cycle Assessment (LCA) is a comprehensive environmental management tool used to evaluate the environmental impacts associated with all the stages of the life cycle of a product, process, or service, from raw material extraction through materials processing, manufacture, distribution, use, repair and maintenance, and disposal or recycling (Finnveden et al., 2009). By considering the entire life cycle of a product, LCA helps to prevent a narrow outlook that might shift environmental problems from one stage to another. Initially, the LCA was primarily restricted to evaluating environmental impacts, as outlined in its foundational frameworks. However, its application has since expanded to include social and economic dimensions.

It is defined by the International Organization for Standardization (ISO) in the ISO 14040 and 14044 standards, which provide a clear framework and guidelines for conducting life cycle assessments. The main purpose of LCA is to assess the environmental aspects and potential impacts throughout a product's life cycle, thereby enabling more sustainable decision-making processes (ISO, 2006a, 2006b).

The LCA process is divided into four main phases: goal and scope definition, inventory analysis, impact assessment, and interpretation (Figure 1.1). Each phase plays a crucial role in ensuring comprehensiveness and reliability of the assessment.

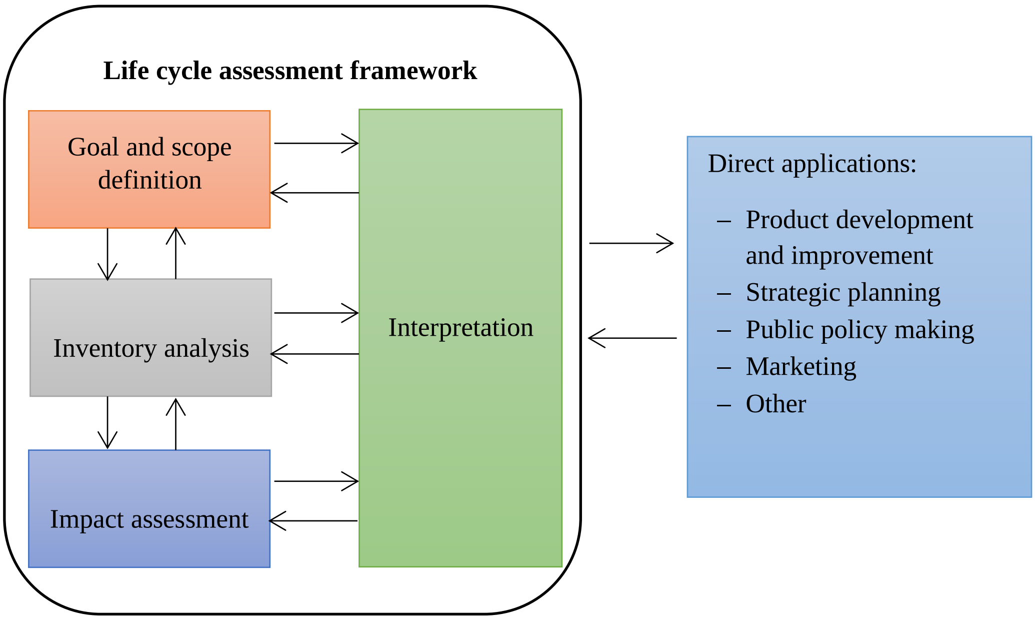

Figure 1.1. LCA Phases. Adapted from (ISO, 2006a)

This tool is widely used across industries and sectors to evaluate the environmental performance of products, processes, and services. It serves as a critical tool in sustainable design, policy making, and marketing, helping organizations to identify opportunities for environmental improvements and informed decision-making (Guinée et al., 2011).

To date, several tools, frameworks, methodologies, and standards have been developed to assess sustainability. However, to attain reliable and robust results, applying the principles of comprehensiveness in a Life Cycle Thinking (LCT), also called the life cycle perspective, is essential. LCT means taking account of the environmental, social and economic impacts of a product over its entire life cycle and value chain (UNEP/SETAC, 2011). Life Cycle Costing (LCC) considers the costs incurred during the lifetime of the product, work, or service, LCA compiles and evaluates inputs-outputs and the potential environmental impacts of a product system life cycle (ISO, 2006a). It is worth mentioning that LCA allows to consider shifting of burdens across geographical areas, and life cycle stages among others.

On the other hand, Social Life Cycle Assessment (S-LCA) is a methodology for evaluating the social impacts of products and services throughout their life cycle, utilizing a combination of modeling capabilities and systematic assessment processes of Environmental Life Cycle Assessment (E-LCA), and methods of the social sciences (UNEP, 2020). Additionally, S-LCA has linkages with international initiatives and can monitor progress in at least seven SDGs: #1, #3 – #5, #8, #10 (Backes & Traverso, 2022), and #12 (Martín-Gamboa et al., 2020). Soltanpour et al. (2019) scrutinize the conceptual underpinnings of S-LCA and the sociological debates on assessing impacts at individual versus societal levels, offering insights into selecting appropriate stakeholders, system boundaries, and indicators in S-LCA, guided by the sociological interpretation of social change quality. Its Area of Protection is Human Dignity (Hauschild et al., 2008) or Human well-being (UNEP, 2020). S-LCA empowers corporate decision-makers to modify products or processes to minimize adverse effects and foster sustainable development without shifting impacts from one life cycle phase to another (Pollok et al., 2021). While S-LCA focuses on the social dimension of sustainability, E-LCA and LCC provide analogous tools for addressing environmental and economic dimensions, respectively.

Nonetheless, existing life cycle-based techniques, which are frequently applied independently, can be combined, performing a Life Cycle Sustainability Assessment (LCSA), evaluating environmental, social, and economic negative impacts and benefits in a product or process life cycle or in decision-making processes (UNEP/SETAC, 2011). It is worth mentioning that the 2020 Guidelines (UNEP, 2020) introduce the Social Organizational Life Cycle Assessment (SO-LCA), which measures social performance at the organizational level, conceptually connecting to Organizational Life Cycle Assessment (UNEP, 2015). This connection emphasizes the broader performance of organizations rather than specific products or processes, distinguishing it from Social Life Cycle Assessment (S-LCA), which aligns with Environmental Life Cycle Assessment (E-LCA) by focusing on individual products or processes. While SO-LCA and S-LCA share the same conceptual foundations, they differ significantly in their scopes: SO-LCA analyzes organizational practices and strategies to evaluate their social impacts holistically, whereas S-LCA assesses the social impacts throughout the life cycle of specific products or services. These complementary approaches provide distinct yet interconnected perspectives on sustainability, with SO-LCA supporting strategic organizational-level decision-making and S-LCA enabling more granular, product-focused insights.

1.4. Technological gaps

Unlike E-LCA, it is notable that currently S-LCA lacks standardization (Ostojic & Traverso, 2024) and code of practice (Arcese et al., 2018). This may be attributed to the methodology's relatively early stage of development (Toniolo et al., 2019), and due to the complex nature of social impacts (Hossain et al., 2018). Standardization is critical and required for the development of more complex methods like LCSA (Zimek et al., 2019), and its absence makes it difficult to compare results across different studies and to ensure consistency and reliability in assessments. An example verse in the field of defining the boundaries and scope, which can be complex. Also, social impacts can occur at various stages of the life cycle and determining which stages to include, and how to account for indirect impacts, is challenging.

According to Pollok et al. (2021), key methodological barriers include: i) lacking comparability and transparency of S-LCA, ii) process vs. organizational S-LCA; iii) generic vs. site-specific data and the dependency on stakeholder participation; iv) tracking social impact pathways; v) neglected stakeholder categories and the variety of impact sub-categories. Additionally, the absence of consensus on social indicators, complexity of social and cultural issues, limited regulation, and nonexistence of technical know-how in social assessment methods are some of the unresolved definitional challenges (Huertas-Valdivia et al., 2020).

In the power sector, these challenges manifest in various forms, such as difficulties in integrating approaches (Nubi et al., 2022a), addressing issues of double-counting (Volkart et al., 2017), and categorizing variables effectively (Khatami & Goharian, 2022). Recent publications have inadequately tackled these concerns, underscoring the pressing need for further methodological advancements in this field.

Among the most critical aspects requiring attention is the selection of social indicators, a pivotal issue in S-LCA (Zanchi et al., 2018). The collection of comprehensive and high-quality social data across supply chains remains a significant obstacle, compounded by the challenges of integrating these data into S-LCA models. Furthermore, the absence of robust tools for quantifying qualitative social impacts introduces inconsistencies and potential biases. Without standardized methodologies for selecting and applying social indicators, results often lack comparability and reliability. Consequently, the prioritization of indicators can appear arbitrary in the absence of clear and robust selection criteria (Haslinger et al., 2024).

The lack of consensus on social indicators is still one of the main challenges of S-LCA (Huertas-Valdivia et al., 2020), and this absence bring significant consequences such as incomparable study results, difficulties in evaluating social performance across different contexts, reduced reliability for policymaking and business decisions, and diminished stakeholder trust, including from consumers and investors. From an alternative perspective, this lack of consensus and standardization allows each study to exhibit unique characteristics, making it more challenging to contest or evaluate. This perception of exclusivity and originality can foster extended discussions and sustain the topic within the theoretical field, providing opportunities for some stakeholders to benefit from this situation.

The power sector could significantly benefit from a well-structured indicator selection framework, as a substantial number of studies lack a clear rationale for choosing relevant social indicators (Ostojic & Traverso, 2024). Developing suitable indicators tailored to the sector, considering temporal, geographical, and technological coverage, while building upon existing methodologies, is therefore essential, particularly for countries with continental dimensions such as Brazil. The selection of S-LCA indicators, particularly in the power sector, remains poorly understood in current literature, highlighting an opportunity for original research with meaningful scientific and technological contributions.

This challenge is further compounded by a significant research gap between global sustainability targets and corporate energy choices. Most approaches treat SDGs as abstract, overarching goals without explicitly aligning them with environmental, social, and technical indicators specific to power generation technologies. As a result, stakeholders often lack practical and measurable pathways to make informed decisions that align with prioritized SDGs, underscoring the need for frameworks that bridge this divide.

Previous studies, such as those by Henzler et al. (2020) and Souza et al. (2022), aimed to integrate SDGs into LCA methodologies; however, they primarily focused on specific regions or a limited set of environmental indicators, lacking a global perspective or a broader range of social and technical indicators applicable to corporations across multiple sectors. Additionally, there is a need to expand the geographical scope to encompass the global power sector and to introduce new indicators quantified based on primary corporate and sectoral data.

Another gap is evident in the work by Hannouf et al. (2023), who presented a qualitative heuristic method to connect LCA categories to SDGs; however, a Multi-Criteria Decision Analysis (MCDA) approach is needed to generate quantitative and actionable insights.

Overall, there is a need for a decision-support framework to aid in selecting electricity technologies constrained by the prioritized SDGs of a corporation or sector, and for quantifying the impacts of electricity generation options aligned with the SDGs, supported by a life cycle approach that integrates social, technical, and environmental aspects of sustainable development. These gaps highlight substantial opportunities for scientific investigation in this sector.

1.5. Objectives

The general objective of this thesis is to assess the sustainability of electricity generation technologies, with a focus on social aspects. This evaluation aims to contribute to the development of decision-making tools that integrate social indicators into sustainability assessments, aligning power sector choices with SDGs.

To achieve this, the study is structured into three specific objectives:

1. Evaluate the status of S-LCA in the power sector, identifying gaps, methodological inconsistencies, and opportunities for improvement in the assessment of social impacts associated with electricity generation technologies - Research line 1 {R1};
2. Develop a social indicator that links different electricity generation options to socioeconomic data, allowing for a more robust assessment of their social sustainability performance - Research line 2 {R2};
3. Propose a decision-support framework for selecting electricity generation technologies aligned with prioritized SDGs for specific sectors and companies, integrating social, environmental, and technical aspects into sustainability decision-making - Research line 3 {R3}.

1.6. Motivation

The ongoing energy transition in the power sector plays a critical role in supporting global initiatives aimed at mitigating climate change and fostering sustainable development. The sector is fundamental to societal advancement; however, its operations are known to produce significant environmental impacts. In this sense, LCA is widely adopted to assess these impacts, especially in the context of increased attention to climate issues and the transition towards sustainable energy.

Nonetheless, focusing excessively on one dimension can lead to the neglect of others. While environmental assessments have made significant strides, there is a risk of overlooking social and economic dimensions, which are equally essential for comprehensive sustainability. To avoid the transfer of burdens from one dimension to others, a more holistic assessment is necessary. It is known that S-LCA can assist in preventing unwanted and sometimes unknown burden shifting from environmental to social sustainability (Koese et al., 2023). Therefore, S-LCA emerges as an option to evaluate the potential transfer of environmental burdens to the social sphere, thus its application should be disseminated and incorporated into socio-environmental analyses of the electric power sector.

This thesis explores S-LCA as a tool to bridge this gap by examining the potential transfer of environmental burdens to social dimensions, an approach that helps prevent unintentional social trade-offs. By expanding the scope of assessment to include social aspects, S-LCA can provide a more holistic view of sustainability in the electric power sector. The motivation for this research lies in the need to enhance S-LCA's application in the power sector, integrating social indicators alongside environmental and technological measures to better inform decisions that align with SDGs. The technological dimension was chosen to substitute the economic one, as Backes & Traverso (2022), found that no LCC indicator could be assignable to SDGs.

This thesis explores specific aspects of originality in the research lines {R1}, {R2}, and {R3}, which are further detailed in three key areas. Firstly, the state-of-the-art in S-LCA methodologies is assessed to identify the main social indicators used in the power sector, alongside key stakeholders and hotspots. This review provides a foundation for verifying existing methodologies and addressing critical gaps in literature.

Secondly, attention is given to the development of practical social indicators that are specifically applicable to S-LCA in the power sector. Recognizing the current scarcity of such indicators, this thesis introduces several innovative metrics, including Manufacturing Employment Rate, Occupational Accidents, Fatalities, Gender Equality, and the Employment-Weighted Fair Wage Potential (E-WFWP), aiming to enhance the implementation of S-LCA in this field.

Lastly, the thesis examines the connections between power options and prioritized SDGs, addressing the need for pathways that integrate the SDG framework into corporate practices. Although SDGs are global or national targets, sectors and companies need a pathway to apply their framework within their organizations or at least align their choices with prioritized SDGs. There are missing links between these goals and S-LCA impact sub-categories (Pollok et al., 2021). According to those authors, breaking down the goals on a corporate level could help companies measuring their individual contribution to the overall transformation. Despite the importance, links between SDGs and S-LCA impact sub-categories remain largely unexplored or are treated superficially in the existing literature. By breaking down SDGs at the corporate level, this work seeks to enable companies to measure their contributions to sustainability more effectively and align their actions with prioritized goals. Therefore, another novel contribution of this thesis is the creation of a methodology that allows a company or sector to select electricity generation technologies that align with prioritized SDGs.

1.7. Outline of Thesis Structure

This thesis is structured as a collection of published and soon-to-be-published articles (Chapters 2, 3, and 4). The research lines {R1}-{R3} are represented by the following distribution given in Table 1.2 (Chapters 2, 3, and 4 fully reproduce their reference scientific articles).

Table 1.2. Scientific articles associated with chapters contents.

Research Line	Chapters	Articles References
{R1} strengthening of S-LCA's role as a decision-making tool	02	In submisson to The International Journal of Life Cycle Assessment (3rd review submitted in october 29, 2024)
{R2} proposition of social indicator to rank energy alternatives	03	Tourinho et al. (2023)
{R3} Power generation technology selection based on Sustainable Development Goals	04	Tourinho et al. (2025)

Chapter 2 critically reviews the S-LCA in the power sector, emphasizing the need for standardized methodologies for better comparative analyses and decision-making. The paper systematically reviews 92 S-LCA studies, identifying inconsistencies in defining system boundaries, functional units, and stakeholder categories. The review highlights the dominant focus on employment and occupational safety indicators, suggesting a need for a broader range of social indicators and stakeholder considerations, including children, to represent future generations. The study underscores the role of S-LCA in advancing the SDGs and the importance of comprehensive assessments that include social dimensions alongside environmental and economic factors in the energy sector.

Chapter 3 (Tourinho et al., 2023) proposes an innovative employment-weighted fair wage potential assessment to identify and implement socially sustainable electricity generation options. The study aligns with SDGs #1 and #8 by focusing on the power sector and evaluating the Fair Wage Potential (FWP) of ten power technologies using a life cycle approach. The study assesses the FWP across different life cycle stages of power generation technologies and introduces the E-WFWP as a new indicator. It calculates this indicator by relating FWP with the number of jobs estimated at each life cycle stage, offering a unique perspective on the social sustainability of power generation options.

Chapter 4 (Tourinho et al., 2025) presents a decision-support framework using LCA to select power generation technologies aligned with prioritized SDGs, incorporating social, technical, and environmental dimensions. The methodology was applied in a case study involving twelve companies from three sectors, demonstrating how businesses can align their power generation choices with their prioritized SDGs. The paper emphasizes the importance of selecting suitable power technologies to support the achievement of SDGs and suggests that companies aligning their strategies with SDGs can better manage risks and build resilience against future shocks.

Chapter 5 presents the discussion related to three papers and the overall subject.

Chapter 6 then finally encloses all studies with an overall conclusion addressing combined discussion of specific results, highlighting the main specific findings of all works.

Appendices A-C are supplementary materials for Chapters 2, 3, and 4.

1.8. References of chapter 1

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2. Social life cycle assessment of the power generation sector: a critical review

Abstract

Purpose: Access to affordable energy is crucial for economic growth and poverty alleviation. Parallelly, transitioning from fossil fuels to alternative energy sources may mitigate climate change, which is a sustainable development goal (SDG#13) but also impacts energy costs (SDG#7) and economic growth (SDG#8). The social dimension is an essential aspect of power generation that influences its overall impact and sustainability. However, the social life cycle assessment (S-LCA) of power systems lacks standardization, impeding effective comparative analyses. Standardized S-LCA boundaries, methods, and indicators are needed to support decision-making on power technologies. This review investigates improvements to strengthen S-LCA's role as a decision-making tool.

Methods: This systematic review employs the Scopus (Elsevier) database and search engine to categorize the selected studies according to predetermined classification criteria, which include publication type, language, and period. The studies must pertain to electricity generation and incorporate at least one power generation technology. The exclusion criterion refined the selection process. The selected studies are analysed for critical components.

Results and discussion: Solar photovoltaic and biomass technologies are the focus of 55% and 54% of the reviewed studies, respectively, being the most researched power technologies. Among the 92 filtered S-LCA works, there is a notable inconsistency in the definition of the system boundary. Approximately 25% of the reviewed S-LCAs do not specify the functional unit, and some are unitless (12%). *Workers* and *the Local Community* are the most assessed stakeholder categories. A total of 49% of the studies employ up to 5 indicators, predominantly concerning *Total Employment*. Multicriteria decision analysis (MCDA) methods are employed in 39% of the articles. Furthermore, 71% of the analysed papers employ an *Impact Pathway Approach*, with 63% applying an empirical method.

Conclusions: This review underscores the critical need for standardized methodologies in S-LCA to foster comparability and facilitate practical application across power sector assessments. By identifying inconsistencies in system boundaries, functional units, and social indicators, this work calls for adopting comprehensive "cradle-to-grave" approaches and the 2020 UNEP Guidelines to enhance consistency. Furthermore, the prioritization of key social indicators like *Total employment*, *Occupational Accidents*, *Public Acceptability*, and *Salary* highlights pressing social issues, reflecting SDGs #1, #7, and #8. These insights aim to guide future research and policymaking toward more inclusive and regionally adapted S-LCA frameworks, supporting sustainable energy transitions aligned with sustainable development goals.

Keywords

S-LCA, Electricity, Power Technologies, Social Impacts, Indicators, Energy, Solar PV, Bioenergy.

Supplementary Materials

Supplementary Materials for this chapter are found in Appendix A.

2.1. Introduction

Societies' concerns with sustainability issues have increased in recent decades, especially since the United Nations (UN) adopted the 2030 Agenda for Sustainable Development in 2015. The UN proposed seventeen sustainable development goals (SDGs) to eradicate poverty, safeguard the environment and climate, and guarantee universal access to peace and prosperity (United Nations, 2018).

Following the 1987 Brundtland Report (Brundtland, 1987), the vision of the environmental, economic, and social pillars supporting sustainable development has become widely accepted. This concept redefines economic growth as a solution to social and ecological challenges, shifting from the original critique of the economic *status quo* (Purvis et al., 2019). Recognizing that the power sector is one of the engines of a country's development (Tourinho et al., 2023) and that the continuous supply of energy and electricity is a prerequisite for the economic progress of a nation (Rashid & Majed, 2023), this sector is also responsible for this pursuit. Strielkowski et al. (2021), for example, highlighted the growing global demand for electric energy and the necessity for decarbonization through renewable energy sources to address climate change, emphasizing the importance of sustainable development principles in the electric power sector. The authors stress how renewable energy not only addresses environmental issues but also has significant social impacts, including job creation, improved energy security, and reduced health risks from pollution. Similarly, Buana et al. (2023) revolves around the critical role of engineers with expertise in power systems in facilitating sustainable energy transitions through active stakeholder engagement and cocreation, underscoring the importance of collaborative efforts among stakeholders to increase sustainability in the electricity sector. Additionally, Pueyo & Maestre (2019) state that access to electricity is a crucial catalyst for economic growth and poverty alleviation in developing nations, propelling economic and social development by boosting productivity and emerging new job-generating enterprises.

Although one of the major objectives of energy development is to transition to a low-carbon and secure energy system (Y. Zhang et al., 2021), decarbonization of the power sector can lead to trade-offs that vary according to the chosen technology (Luderer et al., 2019). Boa Morte et al. (2023) suggest that the energy transition has been driven by SDG#7 (Affordable and Clean Energy) and SDG#13 (Climate Action) while neglecting to assess collateral effects (synergic or antagonistic) on the remaining SDGs. For example, the rising energy costs from deploying renewable energies may preclude economic growth by increasing production costs and limiting consumer spending capacity, influencing SDGs #1, #2, #3, #8, #9, and #11. Climate change requires the reconciliation of various geopolitical interests (Araújo et al., 2024). Effectively applying SDG thinking to the energy sector poses a substantial challenge in targeting efficient and sustainable production systems (Martín-Gamboa et al., 2020).

To date, several tools, frameworks, methodologies, and standards have been developed to assess sustainability. However, to obtain reliable and robust results, applying the principles of comprehensiveness in a Life Cycle Thinking (LCT), also called the life cycle perspective, is essential. LCT involves considering the environmental, social and economic impacts of a product over its entire life cycle and value chain (UNEP/SETAC, 2011). Life Cycle Costing (LCC) considers the costs incurred during the lifetime of a product, work, or service. Life Cycle Assessment (LCA) compiles and evaluates inputs-outputs and the potential environmental impacts of a product system life cycle (ISO, 2006a). Notably, LCA allows the shift of burdens across geographical areas and life cycle stages, among others, to be considered.

Social Life Cycle Assessment (S-LCA) is a methodology for evaluating the social impacts of products and services throughout their life cycle, utilizing a combination of modelling capabilities and systematic assessment processes of Environmental Life Cycle Assessment (E-LCA), and methods of the social sciences (UNEP, 2020). Additionally, S-LCA has linkages with international initiatives and can monitor progress in at least seven SDGs: #1, #3, #4, #5, #8, #10 (Backes & Traverso, 2022), and 12 (Martín-Gamboa et al., 2020). Soltanpour et al. (2019) scrutinize the conceptual underpinnings of S-LCA and the sociological debates on assessing impacts at the individual versus societal levels, offering insights into selecting appropriate stakeholders, system boundaries, and indicators in S-LCA, guided by the sociological interpretation of social change quality, and its *Area of Protection* is *Human Dignity* (Hauschild et al., 2008) or *Human Well-being* (UNEP, 2020). S-LCA empowers corporate decision-makers to modify products or processes to minimize adverse effects and foster sustainable development without shifting impacts from one life cycle phase to another (Pollok et al., 2021).

Nonetheless, existing life cycle-based techniques, which are frequently applied independently, can be combined by performing a Life Cycle Sustainability Assessment (LCSA), evaluating Life Cycle

Sustainability Assessment (LCSA) and evaluating negative environmental, social, and economic impacts and benefits in a product or process life cycle or in decision-making processes (UNEP/SETAC, 2011). Notably, the 2020 Guidelines (UNEP, 2020) include the Social Organizational Life Cycle Assessment (SO-LCA), which measures social performance at the organizational level, complementing S-LCA by going beyond the product perspective. Although SO-LCA and S-LCA are based on the same conceptual grounds, they differ in the scope of the analysis (product vs. organization).

While many studies in LCA have focused on the environmental (Luu et al., 2020) and economic assessment (Naves et al., 2019) of power generation or power generation-related aspects (Wulf & Zapp, 2021), few articles address the social life cycle performance of electricity generation through power systems: nationally with various technologies (Atilgan & Azapagic, 2016), with only one technology (J. Li et al., 2023), or using dozens of indicators (Buchmayr et al., 2022), lacking framework standardization. Notably, social aspects have been investigated via other approaches, e.g., focusing on behavioural aspects (Huckebrink & Bertsch, 2021), social acceptance (Batel, 2020), the internalization of socioenvironmental externalities (García-Gusano et al., 2018), and energy justice (Sovacool et al., 2019).

Wulf et al. (2019), for example, provide a comprehensive survey of the evolution of LCSA while articulating both the recent advancements and prevailing challenges within the field. Visentin et al. (2020) conduct a systematic literature review on LCSA, emphasizing its application, indicators, and methodologies. Tsalidis et al. (2024) conducted a systematic review on S-LCA in electricity generation, analyzing 13 studies on the social impacts of different energy sources, highlighting the predominant focus on workers' rights and local community effects, relying mainly on generic databases. While Chhipi-Shrestha et al. (2015) provide a robust review of the social life cycle impact assessment (S-LCIA) method, their work includes only two papers related to electricity production, highlighting an application gap.

Another clear gap approached by the present work is the lack of standardization in S-LCA, which is in its early stages (Toniolo et al., 2019) due to the complex nature of social impacts, including methodologies, boundaries, and indicators for their evaluation (Hossain et al., 2018). While LCA is well established across sectors, S-LCA lacks standardization, especially in the power sector, whether in integrating approaches (Nubi et al., 2022a), in dealing with double counting (Volkart et al., 2017), or in placing variables in different categories (Khatami & Goharian, 2022). The novel contribution of the present work is the investigation of the state-of-the-art of S-LCA dedicated to the power sector. Specifically, it addresses existing gaps by reviewing applications, boundaries, assessment methodologies, and indicators in power generation technologies, and offers valuable insights of its sustainability and social performance. It also identifies and highlights gaps and inconsistencies within the literature and proposes necessary future developments. The economic and environmental dimensions are not covered, as they are already well established.

2.2. Methods

The systematic review was performed in the Scopus database (Elsevier, 2023). The findings are submitted to the following classification criteria:

(a) Type: article and review published in peer-reviewed journals or conference papers.

(b) Language: English.

(c) Time period: published from 2009 to 2023, with the starting year corresponding to the publication *Guidelines for Social Life Cycle Assessment of Products* (UNEP, 2009);

(d) Fields: titles, abstracts, and keywords.

(e) Application: deal with electricity production, encompassing at least one power generation technology.

(f) Keywords: **{**“Power generation” **AND (**“Social life cycle assessment” **OR** “Social life cycle analysis” **OR** “Social LCA” **OR** “Societal LCA” **OR** “Societal life cycle assessment” **OR** “Societal life cycle analysis” **OR** “SLCA” **OR** “S-LCA” **OR** "Life cycle sustainability assessment" **OR** “cycle sustainability analysis" **OR** “LCSA” **OR** "sustainability assessment" **OR** “sustainability analysis")**} OR {**“Power sector” **AND (**“Life cycle sustainability assessment” **OR** “Life cycle sustainability analysis” **OR** “LCSA” **OR** “Social life cycle assessment” **OR** “Social life cycle analysis” **OR** “Social LCA” **OR** “Societal LCA” **OR** “Societal life cycle assessment” **OR** “Societal life cycle analysis” **OR** “SLCA” **OR** “S-LCA” **OR** “sustainability assessment” **OR** “sustainability analysis”**)} OR {“**Electricity **AND (**“Social life cycle assessment” **OR** “Social life cycle analysis” **OR** “Social LCA” **OR** “Societal LCA **OR** “Societal life cycle assessment” **OR** (“Societal life cycle analysis” **OR** “SLCA” **OR** “S-LCA” **OR** “Sustainability assessment” **OR** “Sustainability analysis" **OR** “LCSA”)**} OR {**“Energy” **AND (**“Social life cycle assessment” **OR** “Social life cycle analysis” **OR** “Social LCA” **OR** “Societal LCA” **OR** “Societal LCA” **OR** “Societal life cycle assessment” **OR** “Societal life cycle analysis” **OR** “SLCA” **OR** “S-LCA” **OR** “Life cycle sustainability assessment” **OR** “Life cycle sustainability analysis” **OR** “LCSA”**)}**;.

(g) Exclusion: Fuel production without electricity generation; not meeting criterion (a) or lacking relevance; and

(h) Scope: The social dimension of LCA in isolation or in combination with the economic and/or environmental dimensions of an LCSA.

The choice to use only the Scopus database was guided by Martín-Martín et al. (2018), whose comparison of major databases – Google Scholar, Web of Science (WoS), and Scopus – found Scopus to have high citation coverage, particularly in engineering (94%) and life sciences (95%). Unlike WoS, Scopus also includes open access journals, making it a comprehensive choice for this review.

The selected references are assessed considering the following aspects: publication year, energy source for electricity generation, geographic distribution, keywords, functional unit, system boundaries, stakeholders, life cycle inventory (LCI), social indicators, impact assessment methods, presence of multicriteria decision analysis (MCDA), and challenges. This survey aims to assess the status of S-LCA in the electricity generation sector and build insights into this domain. The results of the search are presented in section 2.3.

2.3. Results & Discussion

2.3.1. Overview of the literature screening

Before the analysis of the S-LCA phases, an overview is presented to provide general insights into the state-of-the-art of the selected works. In this segment, the papers that fulfilled all the inclusion criteria are presented, including their publication year, geographical distribution, energy source used, keywords, and work context. Sections 2.3.2 to 2.3.5 present aspects related to the LCA phases, such as the most cited functional units and system boundaries, LCI data type, main stakeholders assessed, and applied method of S-LCIA, among others.

The literature screening sketched in Figure 2.1 employed criteria **a** to **f** to filter 1,611 papers. Further refinement based on the abstract information and the exclusion condition (criterium **g**) identified key areas, reducing the ensemble to 130 articles. Further screening with criterium **h** filtered 92 papers to be critically reviewed. Although electricity generation is the only form of energy assessed in the present work, the searched keywords included "energy" to assess the results published in the broader context of energy transition.

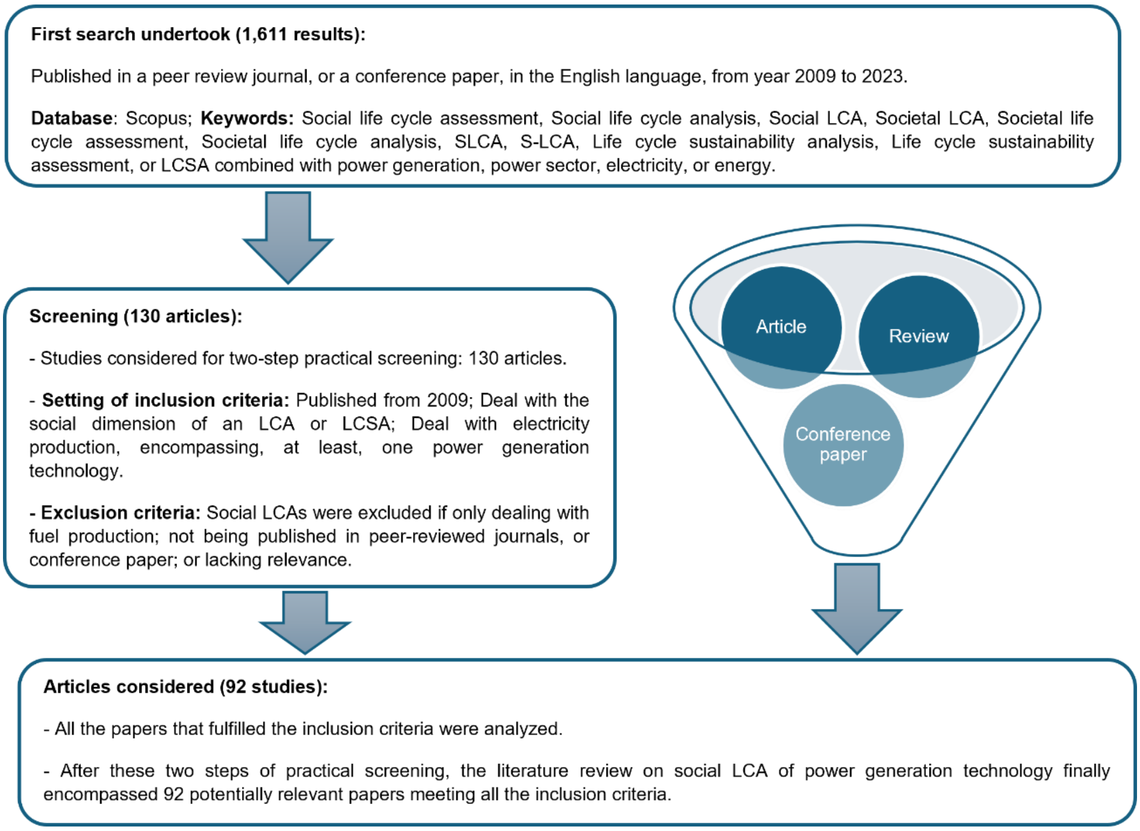

Figure .2.1 Flow diagram for article selection.

Figure 2.2 presents the number of papers by publication year covered by the review, showing the increasing interest in the social aspects of energy systems since 2014. Approximately 70% of the assessed papers conducted a full LCSA in which an S-LCA was included, whereas the other 30% focused exclusively on the S-LCA. An irregular pattern is observed in S-LCA publications during the COVID-19 pandemic (2020–2021), a period characterized by shifts in research priorities and publication dynamics across disciplines, including sustainability and energy studies. This pattern reflects the broader impacts of global events on academic research output. Specifically, the publication rate of COVID-19-focused studies increased substantially between 2020 and 2021, peaking in the second quarter of 2021. In contrast, research on other topics, including S-LCA of power generation, experienced a moderate decline during the same period (Delardas & Giannos, 2022). Similarly, Raynaud et al. (2021) reported a surge in COVID-19-related publications starting in January 2020, accompanied by a decrease in outputs focused on non-COVID-19 topics. Figure 2.2 also shows the cumulative number of papers segregated by energy source, showing an acceleration in the publication rate of S-LCA studies on renewable energy from 2015, when the Paris Agreement was announced at the UN Climate Change Conference (COP21), and the UN launched the SDG.

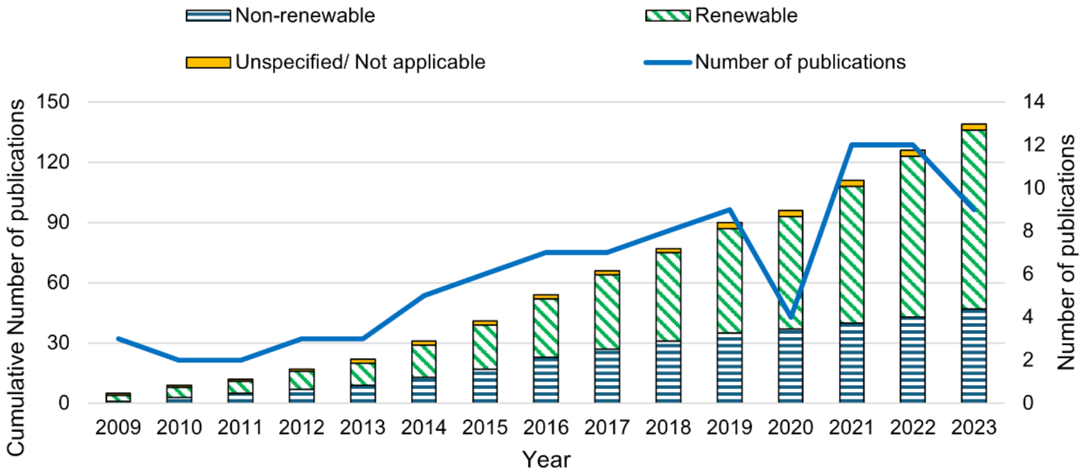

Figure 2.2 Number of publications per year (blue line) and cumulative number of publications related to S-LCA of power generation technologies, typified by the renewability of the energy source.

Figure 2.3 summarizes the energy sources addressed by the studies. While 97% of the literature reviewed covered renewable sources, 51% included non-renewable sources. Solar PV and biomass are the technologies with the highest share of articles, 55% and 54%, respectively, followed by coal (47%), gas (43%) and hydro (41%).

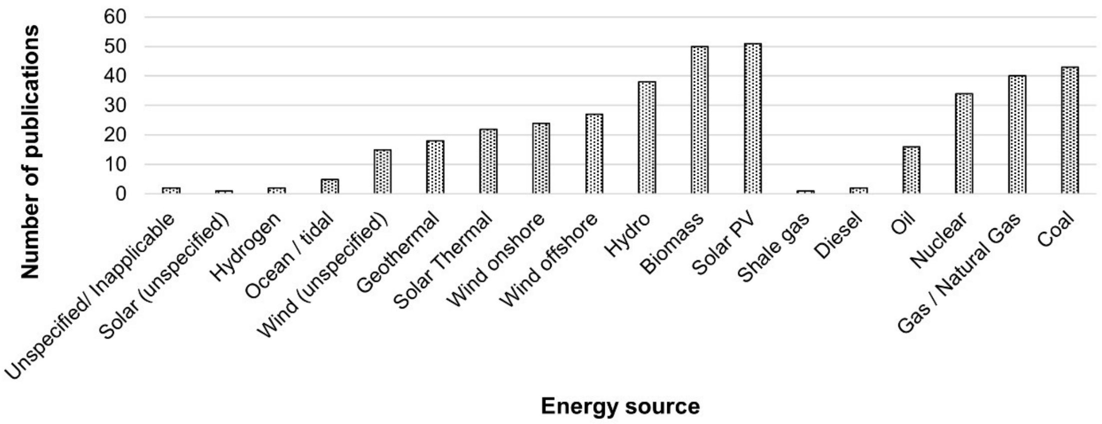

Figure 2.3 Distribution of reviewed publications by energy source.

The geographic distribution of the reviewed articles is available in the supplementary material (Figure S1). In Europe, 57% of the works are from the UK, which leads in awareness of the social aspects of the life cycle performance of energy systems. This could suggest that UK's intensive policies to foster the energy transition are causing concerns about possible social consequences (Department for International Development, 2015). The other regions with the next highest intensity of S-LCA studies are Asian nations (25%) and North America (20%). Some works mention a continent and, occasionally, designate the "world" (9%), whereas 8% of the works do not define the geographical area or are exclusively theoretical approaches.

Figure 2.4 shows a keyword map (built with Gephi, https://gephi.org/) with a minimum threshold of 80 keywords and nodes, providing a comprehensive analysis of the attributes of the literature. Each keyword is a network node, and the larger its representative circle is, the stronger its interactions in the literature. Essentially, if two keywords share a co-occurrence relationship, it implies a connection between the respective nodes in the network. The search structure reveals the predominance of co-occurrences of terms such as life cycle assessment, power generation, electricity generation, and power plants. With respect to keyword frequency, the most frequent keywords are Energy, Electricity, Social, Power, and Sustainability. It is worth noting the appearance of words such as Employment (808 occurrences), Job(s) (625 occurrences), Workers (446 occurrences), Accident (262 occurrences), and Fatality (237 occurrences), indicating relevant issues to stakeholders.

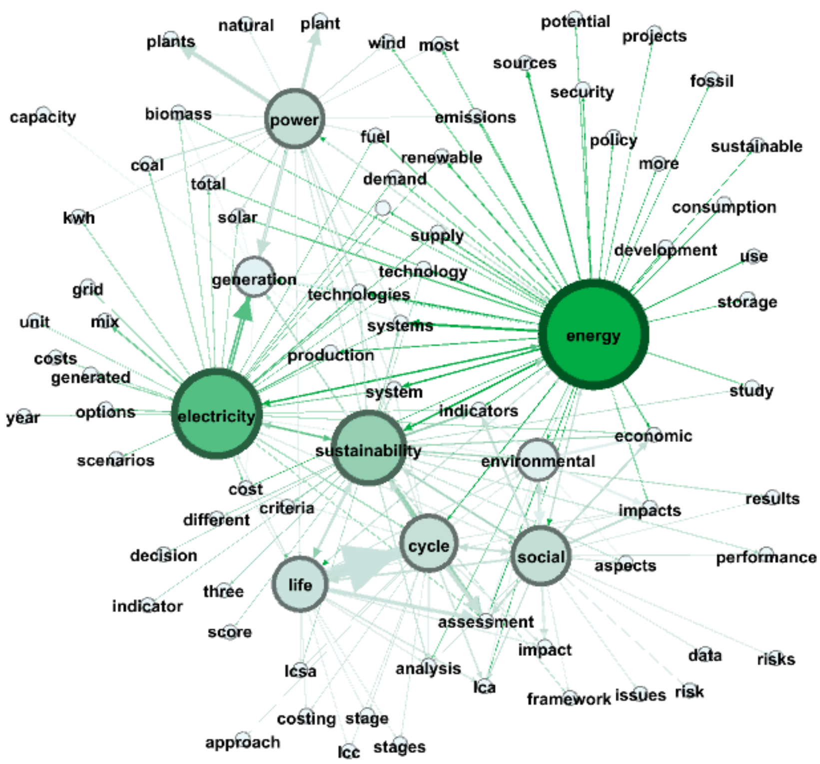

Figure 2.4 Keyword co-occurrence network of the reviewed publications.

A one-phrase abstract was created to synthesize the main objective of each of the 92 selected publications and is shown in Table S1 in the Supplementary Material. Most reviewed works present case studies (47%) or new frameworks or methodologies (45%), the latter suggesting the search for new social impact assessments alone or integrated with other spheres, considering the lack of a standardized framework.

2.3.2. Goal and Scope

2.3.2.1. Functional Unit

A functional unit (FU) is a measure of a product system's performance, used as a reference for consistency in the study's goals and scope (ISO, 2006). In comparative studies, it ensures that different product alternatives are evaluated on an equivalent basis (UNEP, 2020). Defining the FU is also important for determining the reference flow to express specific product flows. Using a common FU enhances consistency, standardization, transparency, and reproducibility in S-LCA studies, making it easier for stakeholders to understand and interpret results. However, finding a suitable FU in S-LCA, especially when integrated with LCA or LCC, can be challenging due to methodological differences and the complexity of addressing multiple sustainability dimensions.

In the present review, 53% of the studies use the amount of electricity generation as the FU (e.g., kW, GWh, MWh, etc.). Notably, 25% of the reviewed S-LCA studies in energy do not specify their FU, and some studies are unitless (12%). As approximately half of the assessed literature considered the amount of electricity generation as FU, the generation of 1 kWh of electricity was the most common unit, applied by 30 papers. Notably, some articles have adopted very specific FUs, such as 'Energy recovery from 1 kg of volatile solids' (Masilela & Pradhan, 2021), '1000 t of sugarcane' (Prasara-A et al., 2019), or 'a concentrated solar power plant' (Backes et al., 2021).

2.3.2.2. System boundary

System boundaries specify which unit processes are part of a product system (ISO, 2006a). Ideally, the system boundaries should be defined from resource extraction to the end-of-life phase (cradle-to-grave). Nonetheless, they can be defined from cradle-to-gate (supply chain of the product or raw material to assembly) or by considering only parts of the life cycle (gate-to-gate or gate-to-grave). Figure 2.5 displays the system boundaries assessed in the analysed literature: 40% (37 papers) use a cradle-to-grave assessment, followed by 27% (25 papers) using a cradle-to-gate approach, whereas 25% (23 papers) have unspecified boundaries. The end-of-life scenario in Figure 2.5 is interpreted as the decommissioning phase of the power plant. It is relevant to observe in the electricity sector that the concepts cradle-to-grave and cradle-to-gate have an unclear threshold among authors. Considering the product as the electricity delivered to the grid, the end-of-life would be the transformation of this electricity into other types of energy: work, heat, and chemical energy.

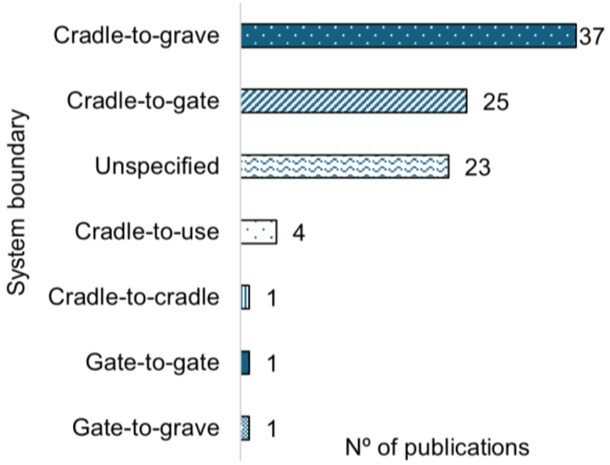

Figure 2.5 Breakdown of system boundaries considered in the portfolio. The numbers assigned to each segment correspond to the absolute count of articles associated with each specified definition of system boundary.

The lack of standardization in defining the boundaries of power generation systems is noticeable. With respect to cradle-to-gate, Corona et al. (2017) exclude electricity transportation and consumption, whereas Luu & Halog (2016) include electricity transmission. Roinioti & Koroneos (2019) and Takeda et al. (2019) consider the boundary extending from resource production to electricity generation but disregard waste disposal or decommissioning after the plant's lifetime. Corona & San Miguel (2019) treat cradle-to-gate spanning material extraction and manufacturing, construction, operation, maintenance, dismantling, and disposal. The same life cycle steps presented by Corona & San Miguel (2019) are named cradle-to-grave by Atilgan & Azapagic (2016), Santoyo-Castelazo & Azapagic (2014), and Stamford & Azapagic (2012). Fortier et al. (2019) describe cradle-to-grave as raw material extraction, components and infrastructure manufacturing, power generation, transportation and distribution of energy and materials at multiple points throughout the life cycle, and waste management. The unusual boundaries, with one occurrence each, are gate-to-gate (Aung et al., 2021), gate-to-grave (Bonilla-Alicea & Fu, 2022), and cradle-to-cradle (Sadhukhan et al., 2021).

Notably, the terminology lacks consistency of thresholds among the studies, as the same term (e.g., cradle-to-grave) is used for boundaries. A consensus should be reached on the system assessed and the life cycle stages considered in the assessments and its terminology. A suggestion is to use the terminology "cradle-to-grave" when referring to the production of an amount of electricity, with the following life cycle stages: material extraction and manufacturing, construction, operation (including fuel production when appropriate), maintenance, dismantling, and disposal.

2.3.2.3. Stakeholders

Stakeholders' classification is fundamental to assess impacts (UNEP, 2021). The 2009 S-LCA Guidelines include categories for *Workers*, *Local communities*, *Society*, *Value chain actors* (e.g., suppliers), and *Consumers* (UNEP, 2009). The 2021 Guidelines introduced an additional category – *Children* – to represent future generations and ensure their welfare (UNEP, 2021), aligning with the Brundtland Report (1987). Most reviewed studies reference the earlier guidelines and do not address the new *Children* category, with only Martín-Gamboa et al. (2022) citing the updated document without specific focus on this group. Table 2.1 shows the main stakeholders cited or inferred based on the social indicators used among the reviewed works. One could infer that citation of the *Next Generation* category in 7 % of the analysed papers suggests a prior call for a look at children as stakeholders, as in the 2021 Methodological Sheets.

Table 2.1 Frequency of citations of the stakeholders assessed by the literature.

	Stakeholders	Number of Occurrences
UNEP SETAC	*Workers*	71
	Local community	55
	Society	53
	Consumers	15
	Value chain actors	9
Others	*University / Research organizations / Scientific experts*	11
	Unspecified / Not Applicable[1]	8
	Government	8
	Enterprises / Companies / Industries	7
	Policy makers	7
	Energy companies / Utility Managers / Private electricity sector	7
	Next generations	6
	Environmental associations / Groups	5
	Non-Governmental organisations (NGOs)	5
	Decision Makers	4
	Local administrations / Council / Community organizers	3
	Institutions (Public, Political or administrative)	3
	Others	26

[1]This category represents the works that are, mainly, theoretical.

The most cited categories proposed by the S-LCA Guidelines are *Workers* (77%), *Local community* (60%), *Society* (58%), and *Consumers* (16%). Among the stakeholders cited, unlike those predicted in the Guidelines, the group *University, Research organizations, and Scientific experts* represent

12% (higher than Value chain actor, with 10%), followed by the *Government* (9%), *Enterprises/Companies/Industries* (8%), Policy makers (8%), and *Energy companies/Utility Managers/Private electricity sector* (8%), which highlights the importance of these stakeholders in the power sector.

2.3.3. Life cycle inventory

The Life cycle inventory (LCI) data can be primary – collected firsthand – or secondary – sourced from other authors or purposes, such as publications, audits, or databases (UNEP, 2020). In the analysed studies, 86% used secondary data, whereas 33% used primary data (alone or in combination with secondary data). Indeed, primary data are often more difficult to obtain, as collecting site-specific information is time-consuming (Corona & San Miguel, 2019) and costly (Aung et al., 2021; Stougie et al., 2015).

A key challenge in S-LCA is obtaining relevant social data, which are often scarce, fragmented, or inconsistently collected. They frequently rely on self-reported information, surveys, or qualitative methods, which can introduce bias, subjectivity, and inaccuracies. Additionally, social impacts vary with factors like geographic location, cultural norms, stakeholder perspectives, and the product's lifecycle stage.

The utilization of databases, websites, statistics, reports, and governmental documents is still the most used source of secondary data and is frequently the basis for the estimation of results. For the analysed articles, frequently assessed sources of secondary data are intergovernmental websites, such as the Food and Agriculture Organization – FAO (Bentsen et al., 2019), the International Labour Organization – ILO (Buchmayr et al., 2022), the International Renewable Energy Agency – IRENA (Atilgan & Azapagic, 2016), and the International Energy Agency – IEA (Evans et al., 2009; Fois et al., 2022). Government reports are also a frequent data source (Atilgan & Azapagic, 2016; Fortier et al., 2019).

The common databases utilized are the *Social Hotspots Database* (SHDB), developed by New Earth (Benoît-Norris & Norris, 2015), and the *Product Social Impact Life Cycle Assessments* (PSILCA), developed by GreenDelta (GreenDelta, 2016). The SHDB is a comprehensive database that maps social risks and opportunities across global supply chains, identifying social hotspots with data available at national, regional, and local levels. It covers a wide range of social issues, integrating information from sources like international organizations, government agencies, NGOs, research institutions, and industry reports. Similarly, PSILCA evaluates and quantifies social impacts throughout a product’s life cycle, offering a holistic view of its social footprint. Data for PSILCA and the SHDB come from industry reports, government statistics, academic research, and stakeholder consultations, with analysis techniques applied to quantify impacts at each life cycle stage. Both SHDB and PSILCA provide social well-being indicators and sector-specific risk assessments that are increasingly used in S-LCA (Buchmayr et al., 2022).

Regarding the specificity of S-LCA databases, the analysis of the reviewed papers highlights a common challenge: the use of generic rather than specific data at the country and sector levels. This generic approach facilitates risk evaluation but limits the potential to analyse specific impacts and compare the performance of different electricity providers within the same country and sector.

Other challenges related to data include difficulties in collection (Corona & San Miguel, 2019), reliability for estimating the potential values of indicators (Cartelle et al., 2015), issues with temporal validity (Guo et al., 2020), uncertainties in MCDA data for ranking alternatives (Ren, 2018), and challenges in quantification (Khatami & Goharian, 2022). Time constraints, budget restrictions (Backes et al., 2021; Yu & Halog, 2015), a lack of site-specific social data (Klein & Whalley, 2015; Stougie et al., 2012), and data insufficiency to obtain reliable interrelationships among criteria (Li et al., 2023) also pose significant issues. Noori et al. (2015) highlight the need for a robust database, and Rodríguez-Serrano et al. (2017) discuss the lack of social risk data in the SHDB for certain countries and sectors, noting the inherent uncertainties related to data collection and conversion of qualitative information into quantitative figures.

Most studies use databases that aggregate data at national or sectoral levels. While helpful for identifying general risks, this approach lacks the details needed to assess specific practices or compare alternatives. This lack of specificity limits precise recommendations or identification of high-performing electricity options. Improved data collection and reporting strategies are essential to close this gap.

Harmens et al. (2021) provide an overview of the primary and secondary life cycle data sources for sector or company information, detailing their key features, including geographic coverage and granularity, data inputs and outputs, and the stakeholders and social impact categories they encompass. As sources of primary data, one can cite Ecovadis (Ecovadis, 2024) and Supplier Ethical Data Exchange – Sedex (Sedex, 2024), whereas Datamaran (Datamaran, 2024) and Maplecroft (Verisk, 2024) are examples of secondary data sources.

2.3.4. Life cycle impact assessment

2.3.4.1. Social indicators

In LCA, a social indicator is either a direct result from the inventory or a subcategory social impact, providing information that helps assess specific social values and goals (UNEP, 2020), and shows how well societal values and goals are being met (Fattahi et al., 2021; Finkbeiner et al., 2010). Initially created to gauge economic growth, social indicators have evolved to assess technological impacts and policy effectiveness (Gallego Carrera & Mack, 2010). In 2005, the UNEP/SETAC Life

Cycle Initiative began developing methodological sheets, with the first set of 31 sheets published in 2010 (Benoît-Norris, 2013). An updated version with 40 sheets and a list of suggested indicators was released in 2021 (UNEP, 2021).

There is no universal set, broadly accepted standard or reference for social indicators (Bonilla-Alicea & Fu, 2022; Bork et al., 2015; Maister et al., 2020; Visentin et al., 2020). The SHDB, for example, comprises 160 indicators (Benoît-Norris et al., 2019), the PSILCA database provides 69 qualitative and quantitative indicators (Maister et al., 2020), and the Methodological Sheets of 2021 suggest 169 indicators: *Workers* – 57; *Local communities* – 31; *Value chain actors* – 16; *Consumers* – 20; *Society* – 29; and *Children* – 16. Importantly, the Methodological Sheets provide only examples, and additional impact categories and indicators can be defined. Many studies, for example, include indicators other than those proposed by the Methodological Sheets and by the S-LCA databases. Figure 2.6 presents the quantities of indicators applied in the studied literature: 49% (45 papers) address up to 5 social indicators per paper, followed by 19% of studies addressing 6 to10 social indicators. Two papers do not address indicators specifically: while Sadhukhan et al. (2021) assess social impacts at the impact category level based on the social hotspot index, Tan et al. (2023) review LCSA solar energy production systems but do not specify the indicators assessed.

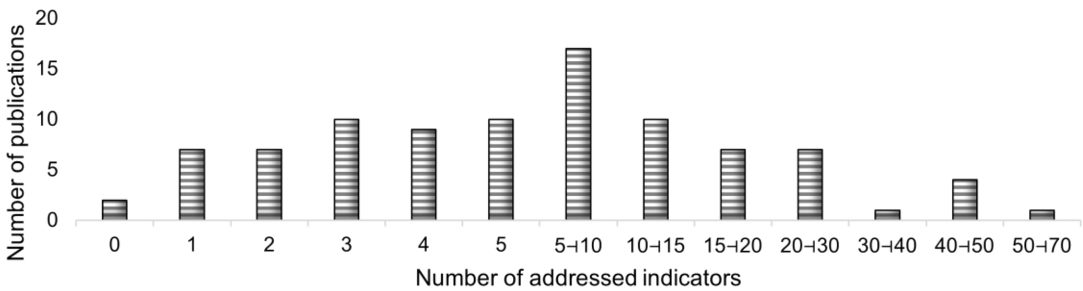

Figure 2.6 Quantities of social indicators addressed by the analysed papers.

Impact categories, subcategories, and social indicators are not uniformly distinguished (i.e., distinct authors use the same term with different meanings). For example, most authors consider the issue of *Health and safety* to be an impact category (Backes et al., 2021; Corona et al., 2017; UNEP, 2020); some authors treat it as a subcategory (Aung et al., 2021; Corona & San Miguel, 2019; Nubi et al., 2021), whereas others consider it more closely to an indicator level: alone (Guo et al., 2020) or adjusted to, e.g., *Occupational health and safety* (Bonilla-Alicea & Fu, 2022; Fois et al., 2022). The same situation occurs with *Local employment*, at times being considered an impact category (Bonilla-Alicea & Fu, 2022; Buchmayr et al., 2022; Y. Zhang et al., 2021), sometimes a subcategory (Aung et al., 2021; Contreras-Lisperguer et al., 2018; Corona & San Miguel, 2019;

UNEP, 2021), and occasionally an indicator (Cooper et al., 2018; Kumar et al., 2023; Vogt Gwerder et al., 2019).

In the present review, the social indicators are considered when specified or indirectly suggested as such by the authors of the analysed publication. More than 400 indicators are mentioned, and Figure 2.7 displays the most cited groups of social indicators (presented in at least 10% of the sampled papers).

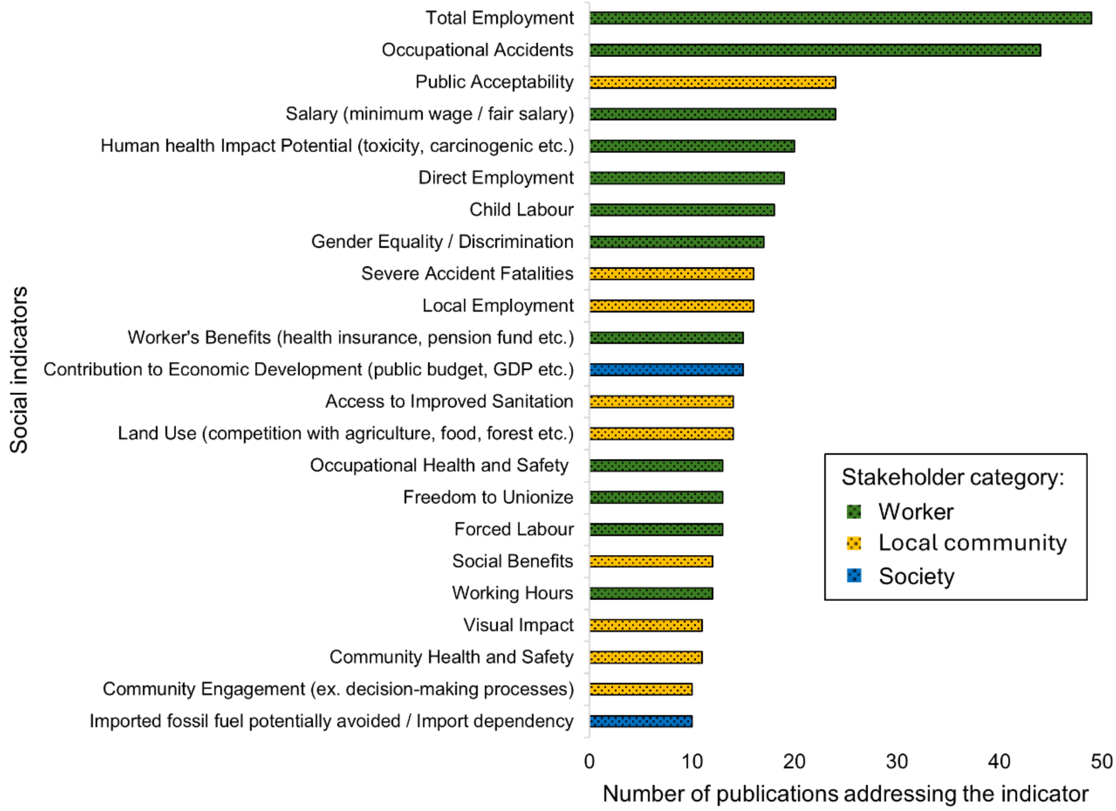

Figure 2.7 Most cited social indicators among the analysed publications.

The indicators are grouped because, despite presenting different terms, their meanings are frequently very similar, e.g., *Total employment*, *Jobs*, *New jobs*, and *Employment generation* were included in the *Total Employment Group*; another exemplification is the group related to *Occupational Accidents*, which encompasses *Number of worker injuries*, *Number of worker fatalities*, *Number of workplace accidents resulting in injuries or death*, *Accident ratio per employee*, among others. It is important to clarify that the aggregation does not necessarily follow the subcategories presented by UNEP (2021) but considers the idea carried out by the cited indicators in the analysed literature. For example, *Fair salary* is a subcategory of the stakeholder category *Worker* in *The Guidelines*; however, it is sometimes cited as an indicator. While Zhang et al. (2021) qualitatively analyse the existence or absence of a fair salary, Backes et al. (2021)

compare the wages in Italy to those in other European countries for the installation of dish-standing concentrating solar power plants. Similarly, *Local employment* is a subcategory of the stakeholder category *Local community* in the *Guidelines;* nevertheless, *Local employment*, as shown in Figure 2.8, considers indicators such as *Local employment created* (Bonilla-Alicea & Fu, 2022), *Local employment* (Cooper et al., 2018), *Promotion of local employment within the project* (Corona & San Miguel, 2019).

Concerning one of the major achievements in the reviewed field related to the social indicators, as noted in Figure 2.7, the most frequent indicators in the power sector for the analysed technologies are related to total employment. Indeed, employment is a key component of economic growth and well-being, permitting people to have money to spend on goods and services, assisting in creating more jobs, and multiplying this cycle, which is a relevant issue for SDGs #1 and #8. This group of indicators is followed closely by occupational accident indicators, reflecting both a significant concern in the literature with this topic and the higher availability of data on workplace accidents and injuries, which are systematically recorded due to regulatory requirements and international reporting standards. The ILO estimates that, annually, approximately 2.3 million people die from work-related accidents and diseases, including close to 360,000 fatal accidents, indicating that the protection of workers against sickness, disease, and injury arising out of their employment is not only a labour right but also a fundamental human right (ILO, 2023).

Notably, 57% of the indicators presented in Figure 2.7 are related to the stakeholder category *Worker*, whereas 35% are related to *Local community*, the main stakeholders affected by the power sector. Issues related to employment, accidents, salary, gender equality, and child or forced labour are frequently analysed in this sector. Likewise, power plants usually occupy a considerable land area, which influences the routine of local communities and can significantly change their lifestyle. Therefore, local community issues such as public acceptability, local employment, access to improved sanitation, community engagement, and indigenous rights are also significantly assessed in S-LCA studies.

With respect to the limitations of indicators, the assessed papers include (a) the absence of clear definitions for some concepts and indicators (Cartelle et al., 2015), (b) the need for quantifiable and straightforward indicators to address robustness and resilience, (c) the requirement for a set of indicators that apply uniformly across assessed products rather than using different sets for each product (Bonilla-Alicea & Fu, 2022), (d) challenges in linking indicators to the FU and validating them (Nubi et al., 2022a), (e) the lack of consensus on the most appropriate indicators (Martín-Gamboa et al., 2022), (f) the need for enhancements in methods and indicators for allowing reliable comparisons (Nubi et al., 2022a), and (g) the use of the same indicators when assessing different populations (Corona & San Miguel, 2019).

2.3.4.2. Impact assessment methods

Social life cycle impact assessment (S-LCIA) aggregates inventory data into specific categories to evaluate social impacts based on a minimum accepted performance level (UNEP, 2021). It consists of (i) selecting impact categories and characterization methods and models, (ii) performing classification, and (iii) performing characterization. According to UNEP (2020), there are two main S-LCA approaches: i) the *Reference Scale Approach* (also known as Type I or *Reference Scale S-LCIA*) and the *Impact Pathway Approach* (also known as Type II or *Impact Pathway* S-LCIA). Type I focuses on product systems' social performance or social risk (UNEP, 2020) and is interpretivism oriented (Iofrida et al., 2018). It uses performance reference points (PRPs), which can be based on different strategies, such as internationally accepted performance levels (norm and best practices), socio-economic contextualization, stakeholder and expert judgment, or comparative approaches (Russo Garrido et al., 2018). PRPs allow the evaluation of the relative position of a dimension's state of a context unit in the face of an international consensus (Parent et al., 2010). It assesses inventory data, expressing positive or negative social performance or high/low social risk (Martín-Gamboa et al., 2020).

The Type I approach presents different impact assessment techniques, but they can be broadly classified into *checklist*, *scoring*, and *database methods* (Chhipi-Shrestha et al., 2015). The checklist method assesses an impact in terms of its presence or absence. In contrast, the *scoring* method uses scores to assess impacts, enabling the indication of an impact level (e.g., low, medium, high) or scale (e.g., 1–very bad, 2–bad, 3–medium, 4–good and 5–very good). In contrast to the *checklist* and *scoring* methods, *database* methods do not employ participatory approaches but rather databases — such as SHDB or PSILCA — and social risk levels (low, medium, high or very high risk) of countries, sectors or stakeholders (Pollok et al., 2021). The database methods also use scores predefined as part of a larger database system (Chhipi-Shrestha et al., 2015).

According to Chhipi-Shrestha et al. (2015), many S-LCA case studies have used the Type I approach. The great variation in their study methods indicates the need to develop a common scoring system. However, the most common Type I method uses scores that easily translate linguistic estimations into numerical values, such as Likert scales (Pollok et al., 2021). Nevertheless, SHDB and PSILCA offer a collection of social well-being indicators and provide risk quantification methods based on involved country-specific sectors, which are increasingly applied as S-LCA methods (Buchmayr et al., 2022).

The type II approach assesses the social impacts derived from the technical nature of the processes (Parent et al., 2010). It is positivism-oriented (Iofrida et al., 2018), aiming to predict the consequences of the product system/organization. It emphasizes characterizing potential social impacts by causal or correlation (regression-based) relationships between the product system/organization activities and the resulting impacts (UNEP, 2020). The core principles of the Type II approach are that social impacts are considered consequences of a change in the life cycle of a product, perceived by affected stakeholders, that can be explained by quantifiable cause–effect relationships (Iofrida et al., 2018). Additionally, it aims to predict the consequences for stakeholders' quality of life and provide generalizable findings.

The impact pathway methods include fewer subcategories and indicators than the *PRP* methods do. The reason might be that Type II methods require quantitative indicators to establish causes and effects to estimate social impacts (Chhipi-Shrestha et al., 2015). Authors searching for new causal links (*empirical relationship pathways*) often follow the Preston pathway, which proposes that increasing economic activity (income) leads to better human health in terms of life expectancy, or the Wilkinson pathway, which describes the relationship between income inequality and health and argues that the unequal distribution of income is harmful to health (Pollok et al., 2021).

Some of the reviewed publications assess social impacts by adapting E-LCIA results as proxies for social indicators. For instance, several authors repurpose indicators that were traditionally classified as environmental indicators, such as Human Toxicity Potential, Depletion of Elements, and Carcinogenic Toxicity, to assess social dimensions related to human health risks, resource availability, and community well-being. According to Chhipi-Shrestha et al. (2015), the use of E-LCIA databases in S-LCIA acts as a methodological bridge between S-LCA and E-LCA. This approach promotes uniformity by aligning functional units, system boundaries, and data sources as much as possible. However, should be emphasized that this method primarily assesses generic impacts, such as health risks and employment effects, while overlooking more nuanced social impacts caused by company-specific behaviours (for instance, governance practices, labour conditions, and stakeholder relationships). These limitations highlight the need for complementary qualitative methods to address aspects that cannot be captured through E-LCIA proxies alone.

The methodological diversity in S-LCIA presents significant challenges regarding categorization and standardization. According to Pollok et al. (2021) although a theoretical categorization of methods is possible, differentiating them in practice is often difficult because researchers frequently apply the same procedural terminology (e.g., classification, characterization, or aggregation) regardless of the method type. Additionally, no common standard exists for how these methods are defined, implemented, or named, leading to inconsistent methodologies and unclear terminology. These issues are compounded by the lack of detailed descriptions of methodologies, which often remain implicit, as noted by (Iofrida et al., 2018). More specifically, Chhipi-Shrestha et al. (2015) emphasize that S-LCIA is still evolving, with no scientific and widely accepted impact assessment framework currently available. The diversity of proposed methods and the absence of standardization may lead to varying results, highlighting the need for further development and refinement.

This lack of standardization and methodological consistency in S-LCIA is particularly evident when examining its application within the power sector. Despite the growing interest in assessing the social impacts of power generation technologies, prior research dedicated specifically to S-LCIA methodologies in this field remains scarce. Sureau et al. (2020) emphasized the need for further methodological development and integration to improve the robustness and applicability of S-LCA. Similarly, Ugaya et al. (2023) highlights that while S-LCA has made significant progress, it still faces methodological challenges, particularly in the quantification of social impacts and the consolidation of Type II approaches. Consequently, the current section presents an overview of the methodologies employed within the reviewed articles, with the objective of elucidating the present status and recognizing emerging trends within this analytical framework. Therefore, the breakdown of the impact assessment methods, based on Chhipi-Shrestha et al. (2015), and considering the contributions of Sureau et al. (2020) and Ugaya et al. (2023), is presented in Figure 2.8 and further detailed in Table S1 in Appendix A. Their distributions over time are illustrated in Figure 2.9, while their detailed classification is depicted in Figure 2.10.

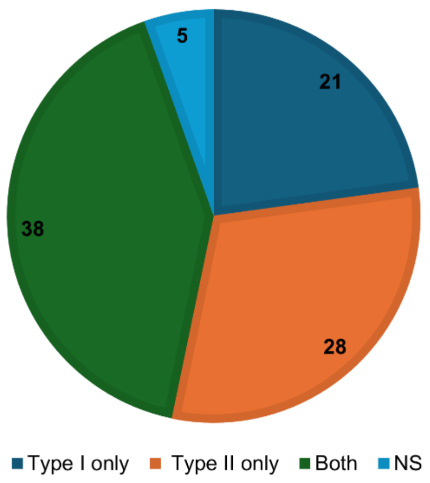

Figure 2.8 Breakdown of impact assessment methods among the analysed papers. Type I = *Reference Scale S-LCIA*; Type II = *Impact Pathway Approach*; NS = Not specified.

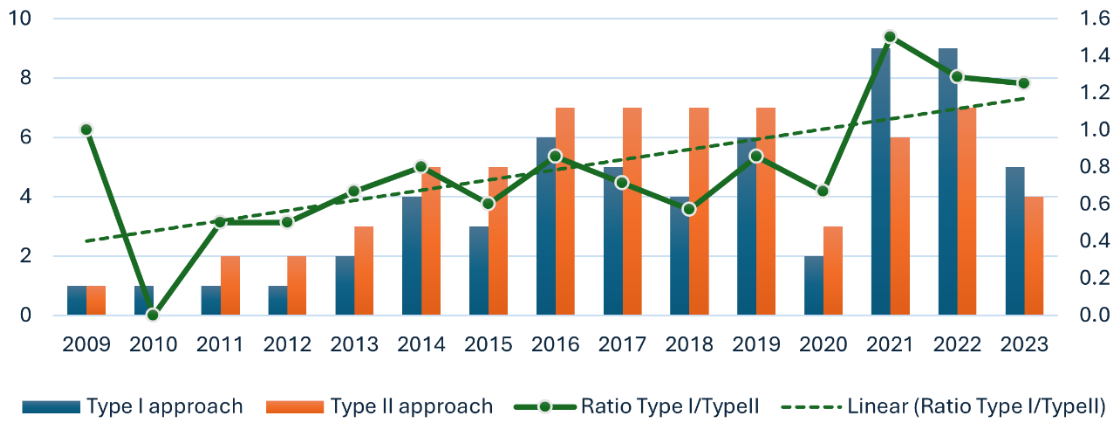

Figure 2.9 Distribution of the impact assessment approach of the reviewed literature over time.

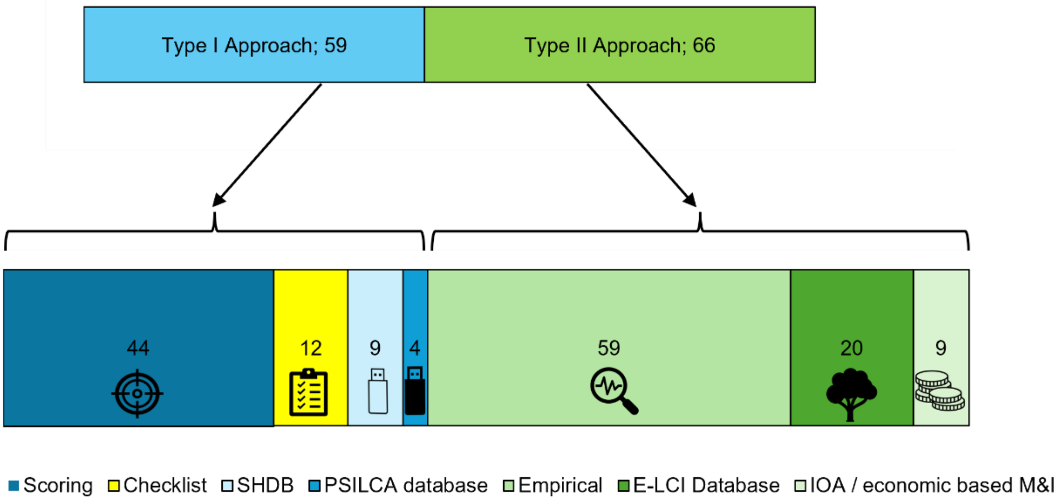

Figure 2.10 Segregation of impact assessment methods among the analysed papers. IOA = input–output analysis; M&I = economic-based methods and indexes; E-LCI = environmental life cycle inventory.

Iofrida et al. (2018) evaluated the diversity of methodological approaches for S-LCA. Their study reviewed 133 publications from 2003-2015, reporting that 73% of the works were ascribed to the group of interpretivism-oriented paradigms (Type I), whereas 24% could be ascribed to the post-positivism group (Type II). Chhipi-Shrestha et al. (2015) stated that many S-LCA case studies have used the Type I approach. However, Figure 2.10 shows that 64% (59 papers) of the analysed literature employed the Type I approach on their S-LCIA, and the Type II approach was adopted by 72% (66 papers); 41% of the analysed literature applied both approaches to assess the chosen indicators (Figure 2.8). Importantly, unlike Iofrida et al. (2018), the present review focuses exclusively on electricity generation in the power sector. As shown in Figure 2.9, both approaches have been utilized in recent years in the studied sector, with a tendency line indicating that the adoption of Type I methods is increasing compared with Type II methods.

A possible explanation for the high adoption of Type II approaches can be elicited from Figure 2.7, which shows that the most cited indicators were related to *Total employment*, *Occupational accidents,* and *Salary*, which in most cases are empirically and quantitatively measured. This logic is corroborated by the results presented in Figure 2.10, where 63% of the examined literature applied the *empirical method*, the most used method among Type II approaches, followed by E-LCI *database methods* (22%) and *economic-based methods* (10%). The latter is composed of input–output analysis (IOA), multiregional input–output analysis (MRIO), environmentally extended input–output (EE-IO), the human development index (HDI), and inequality-adjusted HDI (IHDI), among others. When considering Type I results, as noted by Pollok et al. (2021), the most common method is to use scores. Indeed, the *scoring method* was applied by 48% of the investigated papers (Figure 2.10), followed by the *database method* (14%) and *checklist* method (13%). Among the Type I approaches, 75% of the examined studies used the *scoring method*.

Another significant addition of the present study is the current look to impact assessment methods. Unlike that suggested by Chhipi-Shrestha et al. (2015) and Iofrida et al. (2018), the Type II approach appears to be the most applied type of assessment utilized in the power sector among the studies in the literature.

The presented assessment aims at capturing the state-of-the art of S-LCIA methods applied to electricity generation to assess the impacts of the on the ongoing energy transition. For example, the lack of consensus about the object being assessed – the electricity generated, the power plant, the company, or the delivered electricity – is yet an issue to be discussed. The assessment can be product oriented, focused on the organization's social performance, or even on power technology. The present review addresses this question by presenting the most used indicators, which encompass both technology (e.g., severe accident fatalities and land use) and organization-oriented indicators (e.g., salary and freedom to union), and the most applied type of assessment, the Type II approach.

With respect to methodology, the following challenges exist: the impact of using alternative social impact methodologies/frameworks (Corona et al., 2017); establishing weights for the different indicators (Cartelle et al., 2015); developing a systematic approach to address double-counting (Volkart et al., 2017); and classifying variables into different categories depending on the perspective (Khatami & Goharian, 2022). The project Operational Life Cycle Sustainability Assessment Methodology Supporting Decisions Towards a Circular Economy – ORIENTING – involves multiple European partners, which is producing a variety of outcomes, including evaluation of existing life cycle-based assessment approaches for environmental, economic, and social factors; the development of a robust LCSA methodology; and various tools, including guidance materials and data specifications, to support the methodology's application in business and policy-making (European Commission, 2024). Additional details and updates on the ORIENTING project can be accessed through the Community Research and Development Information Service (CORDIS), a platform providing comprehensive information on EU-funded research projects (European Comission, 2025).

2.3.5. Interpretation

2.3.5.1. Multi-criteria decision analysis

Multicriteria decision analysis (MCDA) are widely used in energy systems for their ability to consider multiple criteria and produce integrated decisions (J. J. Wang et al., 2009), especially when considering the vagueness and ambiguity existing in human judgments (Ren, 2018). According to Volkart et al. (2016), a complete MCDA requires seven steps: 1) selecting technology options; 2) choosing criteria and indicators; 3) quantifying indicators; 4) normalizing data; 5) weighting criteria; 6) aggregating results; and 7) ranking alternatives. There are many types of MCDA methods, and for an overview, refer to Azapagic & Perdan (2005) and Wang et al. (2009). MCDA allows incorporating diverse stakeholders' views into the process through weighting criteria and balancing trade-offs among social impacts resulting from decision options.

MCDA is a powerful tool to address sustainability and energy security issues (Volkart et al., 2016), and in this scenario, 39% of the papers applied an MCDA methodology in their results, especially to rank alternatives. Among the MCDA users, 86% applied it in an LCSA methodology. A complete list of the MCDA methods used in the reviewed literature is available in the Supplementary Material. The predominant methods applied in the reviewed works are multi-attribute value theory (MAVT, 09 occurrences); Analytic Hierarchy Process (AHP, 08 occurrences); Weighted Sum Method (WSM, 05 occurrences); and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS, 03 occurrences).

MAVT involves determining the partial value functions and establishing weights for each criterion to calculate a global value function (Azapagic & Perdan, 2005). The AHP is a widely used decision analysis method that considers both qualitative and quantitative information, arising from the natural human ability to use information and experience for evaluating pairwise comparisons, helping to calculate the relative importance (weight) of individual criteria (Ren et al., 2017). Because individual judgments never agree perfectly, the degree of consistency achieved in pairwise comparisons is measured by a consistency ratio indicating whether the comparison made is sound (J. J. Wang et al., 2009). The WSM is one of the most used MCDA tools because it is simple arithmetic formulae consider specific weights for each indicator to obtain a scalar value for each alternative (Martín-Gamboa et al., 2022). For the TOPSIS method, the chosen alternative should have the profile with the nearest distance to the ideal solution (a composite of the best performance values exhibited by any alternative for each attribute) and farthest from the negative ideal solution (Azapagic & Perdan, 2005).

In the cases where S-LCA is applied together with E-LCA and LCC for the LCSA, enhancing studies by incorporating MCDA methods in the decision-making step (Corona & San Miguel, 2019) is advised, and a cautious selection of the MCDA tool is suggested (Martín-Gamboa et al., 2022). Given the high variability found in technology rankings, the direct involvement of decision-makers in selecting and prioritizing indicators is strongly recommended, including the use of equal numbers of variables for each criterion, to ensure that all aspects receive balanced attention (Khatami & Goharian, 2022). Additionally, Shaaban et al. (2018) recommend validating results, particularly given the broad variation in input data.

While MCDA methods are among the most common and widely recommended strategies, other alternatives also exist. The ORIENTING project outcomes suggest several alternative strategies for integration and aggregation in the LCSA, including multi-objective decision-making (MODM), data envelopment analysis (DEA), visual integration methods such as the Life Cycle Sustainability Dashboard and SEEBalance©, and monetary weighting (Pihkola et al., 2022).

Overall, a few insights emerge from the MCDA used in the assessed portfolio: i) the integration of various sustainability dimensions; ii) its application in diverse fields, including energy policy, urban planning, and infrastructure development, underscoring its utility in handling complex decision problems where multiple criteria are presented; iii) the range of methods used, such as ELECTRE, TOPSIS, G-DEMATEL, and FELICITA, evidence an innovation in methodological approaches and adaptations to specific sectoral contexts; iv) the MCDA helps policymakers and strategists understand trade-offs and make decisions that consider long-term impacts; and v) the importance of stakeholder engagement in the MCDA process includes the complexity of integrating multiple criteria and the subjective nature of weighting and ranking criteria.

2.3.6. Challenges

2.3.6.1. Challenges in the implementation of S-LCA methodologies

One of the key challenges in implementing S-LCA methodologies is the difficulty governmental and policy-making stakeholders face in effectively integrating a life cycle approach into their decision-making processes (Atilgan & Azapagic, 2016, 2017; Roinioti & Koroneos, 2019). Despite growing recognition of the importance of social impact assessment, its adoption remains inconsistent, in part due to fragmented regulatory frameworks and the predominance of economic and environmental priorities in policy agendas. According to Chabrawi et al., (2023), lack of regulatory incentives and institutional integration keeps S-LCA from becoming a mainstream tool. Additionally, S-LCA should be included (either independently or as part of an LCSA) in energy infrastructure planning (Masilela & Pradhan, 2021), but it is often hindered by methodological complexities, data availability constraints, and the absence of standardized assessment tools. The lack of a harmonized approach makes it difficult to compare studies (Nubi et al., 2022), integrate findings into decision-making, and ensure consistency across assessments.

Furthermore, collaboration between stakeholders, decision-makers, and private enterprises to enhance community access to quality services and opportunities remains a challenge (Pérez-Denicia et al., 2021). Disparities in stakeholder priorities (Azapagic et al., 2016), resistance to incorporating social metrics, and difficulties in quantifying and comparing social impacts create barriers to meaningful integration of social considerations into sustainability assessments. Many industries remain reluctant to implement S-LCA due to uncertain benefits and potential reputational risks if assessments reveal poor social conditions in supply chains, for example. Overcoming these obstacles requires not only regulatory improvements but also greater methodological clarity, capacity-building efforts, and financial support to facilitate the practical application of S-LCA in policy and industry.

Another critical challenge is the scarcity and reliability of social data, which often rely on secondary sources that may be outdated, inconsistent, or lacking regional specificity. Collecting primary data is resource-intensive (Aung et al., 2021), requiring time, funding, and access to reliable social indicators at local and national levels. Additionally, there is no universally accepted framework for social indicator selection (Martín-Gamboa et al., 2022) and weighting, making it difficult to establish comparability across studies. The complexity of social impact pathways further complicates assessments, as establishing cause-effect relationships between power generation technologies and social well-being remains a methodological challenge. In general, obtaining universal impact pathways is challenging, given the uncertainty caused by different contexts, time scales, and scales of change (Ugaya et al., 2023).

Securing a sustainable energy supply represents a central political challenge (Gallego Carrera & Mack, 2010). However, the integration of S-LCA into energy policies is further hindered by the lack of institutional incentives and technical expertise. While governments are encouraged to support renewable energy initiatives through increased incentives, funding, investments, and infrastructure development (Roinioti & Koroneos, 2019; Souza et al., 2022; Yu & Halog, 2015), these policies rarely incorporate social sustainability assessments as a core component. The reinforcement of existing renewable energy policies (Santoyo-Castelazo & Azapagic, 2014) and the formulation of strategies promoting recycling, dematerialization, and the use of non-scarce resources (Atilgan & Azapagic, 2017) are important steps, but their social implications remain underexplored in policy design.

Additionally, strategies aimed at skills development and training for large-scale deployment of social sustainability methodologies are essential (Santoyo-Castelazo & Azapagic, 2014; Yu & Halog, 2015), as the lack of technical capacity among policymakers and industry leaders significantly limits the adoption of S-LCA. Promoting awareness of various energy technologies and their integration into existing systems should also include education on S-LCA methodologies (Santoyo-Castelazo & Azapagic, 2014). Without targeted efforts to close these knowledge gaps and establish regulatory mandates, the implementation of S-LCA in the power sector will continue to face barriers, limiting its potential as a decision-support tool for a socially sustainable energy transition.

In the reviewed literature, several methodological challenges related to geography and context-specific factors in S-LCA have been identified. One key issue is the inconsistency in assumptions and the way manufacturing processes are modelled across different studies, which can lead to variations in results (Ko et al., 2018). Additionally, regional differences and national policies influence social outcomes in diverse ways. Since different countries (and even regions within a country) have varying labor laws, worker protections, and social policies, these differences can create inconsistencies in impact evaluation, hindering comparability across studies and making it difficult to apply a uniform assessment framework across multiple locations (Zhang et al., 2021).

Another challenge is the selection of region-specific weights in multi-criteria decision analysis (MCDA), as different regions prioritize social aspects differently, potentially affecting the comparability of results. The integration of spatially explicit LCA is suggested as a way to address localized social impacts more accurately (Souza et al., 2022), as traditional S-LCA methods often rely on global or national averages, which can overlook regional variations in key social indicators, such as wages, labor conditions, employment generation, and human rights enforcement. Furthermore, assessing technologies dynamically, considering how social indicators change over time and across locations, remains a complex task, as the availability and reliability of time-sensitive data are often limited (Shaaban et al., 2018).

Other concerns include the impact of certain power generation technologies on food security, particularly when land or resources are diverted from agriculture (Luu & Halog, 2016), and the need for sensitivity analysis to test how assumptions and input data variations affect the results (Kouloumpis & Azapagic, 2018; Rodríguez-Serrano et al., 2017). Finally, most S-LCA studies focus predominantly on Workers as stakeholders, while broader societal impacts, such as those affecting local communities and future generations, receive less attention (Bachmann, 2013).

Addressing these methodological gaps can improve the robustness and applicability of S-LCA in power sector assessments.

2.3.6.2. Methodological considerations regarding the analysed literature

The primary challenges identified in the literature review is the lack of standardized evaluation structures. Different studies on the same electricity generation technologies employ varying system boundaries, stakeholders, functional units, and types of indicators. Even when the same stakeholders or functional units are used, the impact assessment methods often differ, complicating the comparison or connection of results. These inconsistencies hinder effective decision-making. Additionally, the absence of crucial information in several articles is a significant concern. Some published studies fail to mention the functional units, or the indicators chosen for evaluation, whereas others are purely theoretical or use indicators so specific that they are challenging to apply in other analyses.

2.4. Conclusions and recommendations

The present work focuses on the S-LCA of electricity generation in the power sector, revealing a growing number of studies applying S-LCA in the sector over the years. Reflecting the energy transition, there is a clear trend toward S-LCA of renewable energy, especially solar PV and biomass. Common keywords such as *Employment* (808), *Job* (625), *Worker* (446), *Accident* (262), and Fatality (237) highlight the importance of these issues in S-LCA studies, reflecting their relevance to stakeholders. However, this trend may also be influenced by the availability of secondary data on these aspects, as employment and occupational safety indicators are often well-documented in official databases and reports. Notably, about 45% of the studies introduced new methodologies, suggesting a lack of a widely accepted framework for social evaluation. The review also identifies a significant gap in standardization, especially around system boundaries, functional units, and social indicators, which limits effective comparison and decision-making. To improve comparability, this work recommends using as "cradle-to-grave" boundaries: from raw material extraction to the power plant's end-of-life, as the product is typically the energy delivered to the grid.

Workers and *Local community* are the most studied stakeholder categories, however broader analyses should include others, such as the new *Children* category from the 2020 Methodological Sheets. Regarding LCI, most of the reviewed papers use secondary data, while only 33% use primary data. This general approach supports risk evaluation but limits specific, regional impact analysis. Nonetheless, primary and secondary databases for sector or company information are already available and might help fill these gaps. Most of the studies conducted a full LCSA with S-LCA included, while 30% focused solely on S-LCA, primarily using indicators like *Total employment*, *Occupational Accidents*, *Public Acceptability*, and *Salary*, underscoring critical social issues emphasized in the field. Notably, *Total employment*, *Public Acceptability*, *Direct employment*, and *Land use* are missing from the 2020 Methodological Sheets, highlighting a need for their inclusion. Also, the lack of consistency in defining indicators, categories, and subcategories could be improved by adopting the 2020 Guidelines definitions.

Unlike other sectors, most studies applied a Type II impact assessment approach (72%), with an empirical method (63%), showing a trend of assessing social impacts through causal relationships. S-LCIA is still evolving, with greater depth and method development needed, and regional differences in assessments are essential to consider. Applying weighted criteria in MCDA may address these disparities and support prioritizing social impacts, and notably 39% of the papers used MCDA.

These findings highlight the critical need for standardized methodologies in S-LCA to improve comparability and practical application across the power sector. By adopting consistent FU, system boundaries, and social indicators, future research can more effectively assess social impacts, thereby supporting policy decisions and stakeholder engagement in advancing sustainable energy practices. A recommendation for future S-LCA works is to employ the 2020 Guidelines definitions for category and indicators and adopt the system boundaries presented herein. Stakeholder categories from the 2020 Methodological Sheets, including the Children category and both technology-oriented and organization-oriented indicators, are also advisable. This work aims to serve as a comprehensive guide for researchers, policymakers, and stakeholders in the power sector, offering an overview of the current state of research on social sustainability in power generation and providing actionable guidance for future initiatives. Finally, this review highlights the increasing research focus on the transition to renewable energy within the context of S-LCA. While this transition is challenging, studies increasingly examine how to balance social, environmental, and economic goals, with S-LCA emerging as a key tool to support decision-making and assess sustainability trade-offs in alignment with the SDGs.

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3. Employment-Weighted Fair Wage Potential: A Social Indicator for the Power Sector

Tourinho, T., Araujo, O., & Serra, E. (2023). Employment-Weighted Fair Wage Potential: A Social Indicator for the Power Sector. Journal of Sustainable Development of Energy, Water and Environment Systems, 11(4), 1–26. https://doi.org/10.13044/j.sdewes.d11.0470.

Abstract

Attaining the United Nations Sustainable Development Goals demands a partnership between industrial sectors. The power sector pulls the challenging goal of providing affordable and clean energy to society and industry, each with specific issues. This work recognises the need to address the three dimensions of sustainability and identifies a gap in the literature on indicators to assess the social dimension. In this context, the research presents the employment-weighted fair-wage potential, relating the electricity produced to social data, with ten power technology options. The proposed indicator ranks the alternatives, pinpointing the best technology based on social aspects. The analysis employs a social life-cycle approach with primary and secondary data, worldwide real and living wages, and employment factors. The findings indicate the values of the gas- and oil-based technologies as 3.55 and 3.51 at the operation and maintenance stages, respectively. In contrast, photovoltaics offers the lowest potential value (1.32), followed by biomass-biogas (1.86). Run-of-river emerges as the fairest wage potential option (3.33), followed by the reservoir (2.80), while Solar PV technology presents the lowest value (1.16).

Keywords

Social life cycle assessment, Power generation technologies, Fair wage potential, Employment, Electricity generation, Sustainable development goals.

Supplementary Materials

Supplementary Materials for this chapter are found in Appendix B.

3.1. Introduction

The Sustainable Development Goals (SDGs) are a universal call to action to end poverty, protect the environment and climate, and ensure that people everywhere can enjoy peace and prosperity (United Nations, 2018). For the countries to achieve the SDGs, different sectors should participate in this quest. Considering that the power sector is one of the engines of a country's development, it is also responsible for participating in this pursuit. Implementing the SDG philosophy in the energy sector is a significant challenge for achieving efficient and sustainable production systems (Martín-Gamboa et al., 2020). Access to electricity is increasingly recognised as a critical enabler of economic growth and poverty reduction in developing countries, driving economic and social development by enhancing productivity and enabling new types of job-creating enterprises (Pueyo & Maestre, 2019). According to Mastoi et al. (2022), renewable energy is currently argued as the most prominent solution to environmental pollution, the energy crisis, and social sustainability, being also key element to support sustainable development and a social contributor to people living in isolated communities (Jean & Brasil Junior, 2022).

While many studies have focused on the environmental and economic assessment of power generation (Geller & Meneses, 2016; Gemechu & Kumar, 2022; Hemeida et al., 2022; Naves et al., 2019), or power generation related (Wulf & Zapp, 2021), fewer articles address the social life-cycle performance of energy supply systems(Atilgan & Azapagic, 2016; Buchmayr et al., 2022; J. Li et al., 2023; Stamford & Azapagic, 2012). A clear research gap exists in considering social issues in such assessments. Despite deep decarbonisation being a critical pillar in the power sector for a carbon-neutral energy system, its socioeconomic benefits remain unexplored (Luo et al., 2023). In this context, Social Life Cycle Assessment (S-LCA) emerges as a tool to evaluate the social aspects associated with the life cycle of goods and services and to identify the hotspots of social risks in the energy value chain (Corona et al., 2017). Life Cycle Assessment (LCA) is the compilation and evaluation of inputs, outputs, and the potential environmental impacts of a product system throughout its life cycle (ISO, 2006a). Hence, S-LCA can be considered a methodology to assess the social impacts of products and services across their life cycle, employing the Environmental Life Cycle Assessment (E-LCA) combined with social sciences methods (UNEP, 2020). Additionally, S-LCA has linkages with international initiatives and can monitor progress in ten SDGs (especially SDGs 8 and 12) (Martín-Gamboa et al., 2020).

The utilisation of S-LCA as a social sustainability assessment tool is still being developed due to the complex nature of social impacts (Hossain et al., 2018). Currently, those impacts are understood as the positive or negative consequences of the causal relationship between an activity and an aspect relating to human well-being, as covered by impact subcategories (UNEP, 2020). These subcategories must, indirectly, be related to the stakeholders, i.e., individuals or group that has an interest in any decision or activity of an organisation (ISO, 2010), while the stakeholder category is a cluster of stakeholders having common interests due to their similar relationship to the investigated product system (UNEP, 2020). The main stakeholder categories considered in the S-LCA are Workers, Local communities, Value chain actors (e.g., suppliers), Consumers, Children, and Society. Because impact categories are broad themes, a life-cycle initiative project group created by UNEP/SETAC in 2004 has focused its initial effort on identifying and building consensus around subcategories that describe more precisely social areas of interest (Benoît et al., 2010). Social and socio-economic subcategories of impact have been defined according to international agreements and international best practices, presented in Table 3.1.1 and published in the Guidelines for Social Life Cycle Assessment of Products (UNEP, 2009). In Table 3.1., Fair Salary, a subcategory of the impact category Working Conditions, relates to SDGs 1 and 8 (UNEP, 2020).

A fair wage is a topic that influences all stakeholder groups identified within the S-LCA guidelines. However, studies considering the wage issue are rare in the electricity sector in S-LCA scopes. Fortier et al. (Fortier et al., 2019) discuss how social LCA can address energy justice for stakeholder categories across the life cycle of electrical energy systems and analyse whether wages are docked by companies for reasons beyond a worker's control, wage gaps between sex, gender, nationality, and race; and the percentage of workers earning a living wage based on their location. Traverso et al. (Traverso et al., 2012) report the sustainability assessment of the assembly step of photovoltaic (PV) modules production by Life Cycle Sustainability Assessment (LCSA) and included indicators like the average wage of male and female workers and the minimum wage of a worker. Contreras et al. (Contreras-Lisperguer et al., 2018) assessed the impacts of the bagasse cogenerated bioelectricity using LCSA and encompassed, among the indicators, Lowest Paid Workers, compared to the country's Minimum Wage. Prasara-A et al. (2019) identify the environmental, socioeconomic, and social hotspots of products within the Thai sugar industry (e.g., bagasse-based electricity) using LCA and S-LCA, including the indicators Range of Wage Received by Workers, and Percentage of Workers Satisfied with Wage.

Considering this background, a fair wage is a concept that goes beyond the notion of a minimum wage enabling needs satisfaction and including the fair remuneration of work according to its quality (Pereirinha & Pereira, 2023). It has already been listed as one of the meaningful aspects to be considered in assessing labour rights and decent working conditions, being highly relevant for the future development of human beings and, consequently, of regions and countries, as the basis for prosperity and wealth (Neugebauer et al., 2014).

A "fair" remuneration along the life cycle of a product can serve as one powerful measure to estimate related social impacts on involved workers. In this context, Neugebauer et al. (2017) proposed Fair Wage as a new midpoint impact category and developed a characterisation model to convert inventory data on workers' remuneration along a product's life cycle into category indicator results, creating the Fair Wage Potential (FWP) indicator. FWP considers the actual wage paid at each process step, compared to a minimum living wage, and relates wage to the effective working time, including a factor to account for income inequalities.

Table 3.1. Stakeholder categories and subcategories (Benoît et al., 2010)

Stakeholder categories	Subcategories
Stakeholder "worker"	Freedom of association and collective bargaining Child labour Fair salary Working hours Forced labour Equal opportunities/discrimination Health and safety Social benefits/social security
Stakeholder "consumer"	Health and safety Feedback mechanism Consumer privacy Transparency End of life responsibility
Stakeholder "local community"	Access to material resources Access to immaterial resources Delocalisation and migration Cultural heritage Safe and healthy living conditions Respect of indigenous rights Community engagement Local employment Secure living conditions
Stakeholder "society"	Public commitments to sustainability issues Contribution to economic development Prevention and mitigation of armed conflicts Technology development Corruption
Value chain actors (excluding "consumers")	Fair competition Promoting social responsibility Supplier relationships Respect of intellectual property rights

The method proposed by Neugebauer et al. (2017) is a distance-to-target impact pathway (UNEP, 2020) and can be summarised according to Equation (3.1):

$$FWP_n = \frac{RW_n}{MLW_n} \times \frac{CWT_n}{RWT_n} \times (1 - IEF_n^2) \tag{3.1}$$

where FWP_n is the Fair Wage Potential (expressed in FW_{eq}) representing the n^{th} process within a product's life cycle at a defined location or sector; RW_n is the Real (average) wages (€/month calculated over one year), which are paid to the worker(s) employed in the n^{th} process; MLW_n is the Minimum living wage (€/month), which has to be paid to the worker to enable an adequate living standard for an individual and/or family in the respective country or region/sector where the n^{th} process is performed; CWT_n is the contracted working time per country or sector (hours/week) for workers performing the n^{th} process (including vacation days); RWT_n is the real working time (hours/week) of workers performing the n^{th} process (including vacation days and unpaid overtime); IEF_n is the (squared) inequality factor (expressed in percentage) of the organisation region, country or sector, where the n^{th} process is performed. For RW_n and MLW_n, the national currencies are used in Equation (3.1). FWP depends on mainly three country/region-specific and/or product-specific parameters: 1) living wages, 2) working time, and 3) income (in-)equality (UNEP, 2020).

If the RW_n value is smaller than the MLW_n value, the resulting FWP_n will be < 1; hence the greater the distance from the (minimum) targeted state, the lower the FWP_n value is. Also, if the real working time is equal to the CWT value, then no effect on the FWP_n occurs. On the other hand, if the RWT value is greater than the CWT value (which indicates overtime work), the resulting FWP_n will also be < 1 (smaller FWP_n values indicate more overtime the worker does). A FWP_n equal to 1 (one) is the reference value for determining a fair wage; values >1 mean the salary is fair. An accumulation of FWP values <1 may indicate regular annual underpayment (Neugebauer et al., 2017). Thus, a determined distance from fair wage is a category indicator for the impact category Fair Wage. Excessive working hours may additionally contribute to cases of underpayment through time lost to replace the lack of income.

The methodology by Neugebauer et al. (2017) allows for consistently determining fair wage impacts along a product's life cycle. However, the characterisation model does not foresee a direct relation to the functional unit. Vitorio Junior & Kripka (2020) propose a weighted fair wage potential method to assess building typology and relate material inventory to the social data of the construction sector. However, a knowledge gap remains in the methodology to assess the energy sector, linking the FWP to electricity production.

The present work aims at fulfilling this gap by proposing an Employment-Weighted Fair Wage Potential (E-WFWP) indicator based on the characterisation model presented by Neugebauer et al. (2017). It differs from the existing social assessment methods by relating the electricity production alternatives to social data, allowing the consideration of social aspects in selecting the best choice among a set of analysed options. Additionally, the study performs an S-LCA of ten power generation technologies, considering their E-WFWP to identify the wage situation of workers involved in the electricity system, searching for social hotspots (well-being threats). It proposes and applies a decision-support indicator based on fair wages, in alignment with SDGs 1 and 8, underpinned by a life cycle approach.

3.2. Materials and Methods

This section presents the premises for selecting electricity technologies, the S-LCA parameters, and the data-gathering procedure. The methodology used is described as follows.

3.2.1. Electricity technologies selection

The main electricity generation technologies currently in use worldwide are solar photovoltaic (solar PV), large hydropower plants (reservoir), small hydropower plants (Run-of-River – R-o-R), onshore wind, offshore wind, oil, gas, coal, nuclear, and biomass (biogas).

3.2.2. Social life cycle assessment

S-LCA presents a systematic assessment process like that of the E-LCA. This subsection presents the definition of objective and scope, life cycle inventory, and premises.

Definition of objective and scope. The present S-LCA aims to assess the potential of alternative power generation technology to offer a fair wage to the workers' category along the life cycle of electricity generation. The Functional Unit (FU) is 1 TWh of produced electricity. The scope of the power plant analysis is cradle-to- grave, and encompasses the stages presented by Rutovitz et al. (2015), i.e., the power station construction and installation, manufacturing of parts, operation & maintenance (O&M), decommissioning, and fuel extraction and processing.

A product system is a collection of unit processes with elementary and product flows, performing one or more defined functions, and which models the life cycle of a product (ISO, 2006b).

Figure 3.1 presents the product system of the study, as well as its system boundary. It can be observed that the extraction of primary resources and waste treatment and disposal are outside the scope of this analysis.

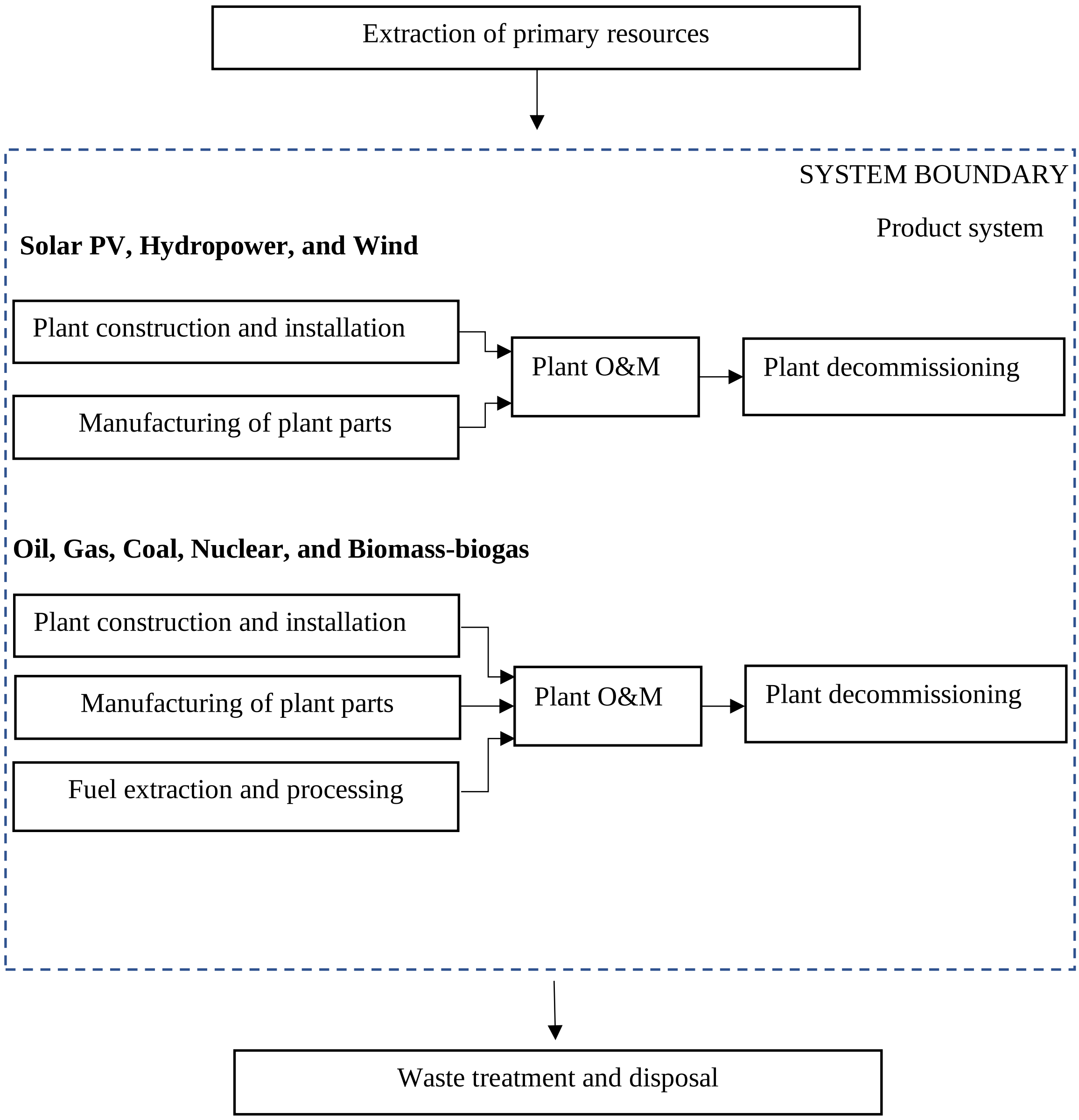

Figure 3.1. Product system and system boundary of the study

Life-cycle inventory data. Primary and secondary data are gathered for the life cycle inventory (LCI) phase. Table 3.2 displays the technical assumptions for each power technologies alternative. The installed capacity values presented in Table 3.2 are the theoretical necessary capacities, considering the efficiencies also presented in Table 3.2, to meet the production of 1 TWh/year (the functional unit). The data of the world installed capacity for each power technology is based on the world breakdown of the technology's installed capacity in 2020 (International Energy Agency, 2020; International Renewable Energy Agency (IRENA), 2020a; Pitteloud, 2021).

Table 3.2. Summary of life cycle inventory data and assumptions

Power options	Power plant assumptions			
	Lifetime	Efficiency	Installed capacity	Breakdown of the world installed capacity
Solar PV	30 years (Dones et al., 2007)	25% (EPE, 2020)	456.6 MW	China - 36.0%, USA - 10.7%, Japan - 9.5%, Germany - 7.6%, Italy - 3.1%, Australia - 2.5%, South Korea - 2.1%, Spain - 2.0%, RoW [1] - 26.7%
Hydro (Reservoirs)	150 years (Dones et al., 2007) (Atilgan & Azapagic, 2016)	78% (Dones et al., 2007)	146.4 MW	Brazil - 9.5%, USA - 7.3%, Canada - 7.0%, Russia - 4.4%, India - 4.0%, Norway - 2.9%, Turkey - 2.7%, Japan - 2.4%, France - 2.1%, RoW - 57.8%
Hydro (R-o-R)	80 years (Dones et al., 2007) (Atilgan & Azapagic, 2016)	82% (Dones et al., 2007)	139.2 MW	USA - 7.3%, Canada - 7.0%, Russia - 4.4%, India - 4.0%, Turkey - 2.7%, Japan - 2.4%, France - 2.1%, RoW - 70.1%
Onshore wind	20 years (Dones et al., 2007) [2]	20% (Dones et al., 2007)	570.8 MW	China - 46.4%, USA - 20.0%, Germany - 9.3%, India - 6.6%, RoW - 17.8%
Offshore wind	20 years (Dones et al., 2007) (Stamford & Azapagic, 2012)	30% (Stamford & Azapagic, 2012)	380.5 MW	UK - 30.2%, China - 26.2%, Germany - 22.5%, Netherlands - 7.3%, RoW - 13.8%
Oil	30 years (Akber et al., 2017a)	40% (Stamford & Azapagic, 2012)	285.4 MW	China - 28.2%, USA - 16.2%, India - 7.4%,

				Japan - 4.9%, Russia - 4.2%, RoW - 39.0%
Gas	30 years (Kabayo et al., 2019; Roinioti & Koroneos, 2019)	38% (Dones et al., 2007)	300.4 MW	China - 28.2%, USA - 16.2%, India - 7.4%, Japan - 4.9%, Russia - 4.2%, RoW - 39.0%
Coal	30 years (Dones et al., 2007), (Kabayo et al., 2019)	36.5% (Kabayo et al., 2019)	312.8 MW	China - 50%, USA - 13%, India - 11%, RoW - 25%
Nuclear	40 years (Dones et al., 2007)	80.4% (Dones et al., 2007)	142.0 MW	USA - 25.0%, France - 16.1%, China - 11.6%, Japan - 8.1%, RoW - 39.2%
Biogas	25 years (Jungbluth et al., 2007)	33% (Jungbluth et al., 2007)	345.9 MW	Germany - 37%, USA - 11.4%, UK - 9.2%, Italy - 7.1%, Turkey - 3.7%, RoW - 31.6%

[1] RoW – Rest of the World; [2] lifetimes of the moving parts

3.2.3. Fair wage potential

The FWP indicator applied in this study is an adaptation of the indicator proposed by Neugebauer et al. (2017). The FWP is obtained using Equation (3.1). The RW_n, MLW_n, CWT_n, and RWT_n values for the construction and decommissioning (C&D), manufacture, fuel extraction, and processing are obtained from the "Fair wage characterisation" file provided by the Technischen Universität Berlin (TU Berlin) (Neugebauer, 2016), and shown in Table A1 in the Appendix. Considering the countries presented in Table 3.2, Brazil, India, and Italy lacked data on construction, manufacturing, fuel extraction, and processing values. In these cases, additional research was carried out on specialised websites (Departamento Intersindical de Estatísticas e Estudos Socioeconômicos (DIEESE), 2013; Ministério do Trabalho (Brasil), 2021; Payscale, 2021k) and updated according to inflation (Banco Central do Brasil, 2021; Inflation Tool, 2021; Investing.com, 2021; Ministério do Trabalho (Brasil), 2021). For the IEF_n values, 2020's Gini Coefficients are considered for each country (Statista, 2021b). As a premise, the foreign workforce was not contemplated in the analysis, considering that globally migrant workers constituted 4.9 % of the labour force of destination countries in 2019 (International Labour Organization, 2021).

Regarding the O&M stage, there is a lack of RW_n data in TU Berlin's file. In this case, Equation (3.1) calculates the FWP employing the data found for each company in a country. RW_n values for each analysed country considering different power technologies are calculated from spread information. Income data are from specialised websites when available (Payscale, 2021k). Data related to "Living Wages" are from dedicated websites (Oxfam Hong Kong, 2018; The Living Wage Foundation, 2021; WageIndicator.org, 2021). Table A2 in the Appendix compiles the aforementioned factors' values. Currency values are corrected due to inflation based on information from specific websites that estimate each country's inflation (Macrotrends, 2021; Statista, 2021a), and values are presented in Table A3 in the Appendix.

Whenever the wage value for a given power technology is unknown, the country's workforce for this specific technology is considered. For the chosen countries, power companies that present a significant rate of their electricity generation portfolio in the form of the studied power technology are selected and analysed. Wage data is collected by means of the available reports for each company, i.e., annual/ financial/ consolidated/ or Corporate Responsibility reports. In all cases, the most recent published reports are considered. The wage reported in each document was compared with the country's minimum wage for the reference year of the report. The average values found for each company within the same country were calculated. Next, the weighted average wage among the analysed countries for the specific power technology was estimated, and this value was extrapolated to the rest of the world.

3.2.4. Employment

In this study, employment is the sum of direct jobs, i.e., the number of jobs during construction and installation, O&M, and decommissioning, plus indirect jobs, i.e., related to fuel extraction and processing, in the case of thermal power, as well as in the manufacture of plant parts (Atilgan & Azapagic, 2016). The unit of this indicator is "jobs-year", that is, the number of people employed for a whole year in a complete working day. The measurement procedure is based on Atilgan and Azapagic (2016), Stamford and Azapagic (2011), and Roinioti and Koroneos (2019). Employment for each technology is estimated, for different life cycle stages, using the employment *factors* (EF_i) compiled by Rutovitz et al. (2015). Employment factors for the selected power technologies are presented in Table 3.3. The factors presented in Equation (3.2) and Table 3.3 allow the calculation of the total employment:

$$TE = \frac{\sum_i^J C_t \times EF_i \times d_i}{P_{tot}} \tag{3.2}$$

where TE is the total employment provision over the life cycle of a given energy technology (jobs-year/TWh); C_t is the installed capacity of an energy technology (MW); EF_i is the employment factor in the i^{th} life-cycle stage (jobs-year/MW); d_i is the duration of employment in the i^{th} life cycle stage (years); P_{tot} is the total amount of energy generated over the lifetime of energy technology (TWh); J is the total number of life cycle stages; and i is the life cycle stage.

Employment in each life cycle stage at a given technology is calculated similarly to TE, although considering only the employment factor of that stage, i.e., construction and installation; manufacturing; O&M; or fuel extraction and processing. For calculating jobs created in the decommissioning stage, it is considered that it employs 20% of the number of workers in the construction stage (Atilgan & Azapagic, 2016). Other premises, like efficiency, annual electricity generation, and installed capacity, are presented in Table 3.2.

Table 3.3. Employment factors for different power technologies

Power technology	Construction and installation (jobs-year/MW)	Manufacturing (jobs-year/MW)	O&M (jobs/MW)	Fuel extraction and processing (jobs/PJ)
Solar PV	13.00	6.70	0.70	-
Hydro (Reservoirs)	7.40	3.50	0.20	-
Hydro (R-o-R)	15.80	10.90	4.90	-
Onshore wind	3.20	4.70	0.30	-
Offshore wind	8.00	15.60	0.20	-
Oil	1.30	0.93	0.14	8.60
Gas	1.30	0.93	0.14	8.60
Coal	11.20	5.40	0.14	40.10
Nuclear	11.80	1.30	0.60	0.001 (jobs/GWh)
Biogas	14.00	2.90	1.50	29.90

3.2.5. Employment-Weighted Fair Wage Potential

By relating the FWP with the number of jobs estimated in each life cycle stage, the Employment-Weighted Fair Wage Potential (E-$WFWP_t$) of a t technology is calculated with Equation (3.3):

$$E - WFWP_t = \frac{\sum_i^J FWP_i \times E_i}{TE} \qquad (3.3)$$

where E-$WFWP_t$ is the employment-weighted fair wage potential over the life cycle of a given energy technology; FWP_i is the fair wage potential on the life-cycle stage i; E_i is the employment provision in life-cycle stage i (jobs-year/TWh); TE is the total employment provision over the life cycle of a given energy technology (jobs-year/TWh); J is the total number of life cycle stages; and i is the life cycle stage.

The E-$WFWP_i$ is a weighted average of the FWP_n values for a life cycle stage i, considering each country's contribution to the number of jobs worldwide available for the power technology or its installed capacity. The intended results indicate the wage situation of the analysed power technologies. As in the FWP_n, the E-$WFWP_i$ presents a distance-to-target impact pathway, where values smaller than 1 indicate unfair wages, while values greater than 1 suggest fair wages.

3.3. Results and Discussion

This section presents the results of each step of the assessment process.

3.3.1. Fair wage potential

The FWP_n is calculated using Equation (3.1). Table 3.4 shows the results of FWP_n for the construction, decommissioning, manufacturing, and fuel extraction and processing stages in the analysed countries. The complete data set, including RW_n, MLW_n, CWT_n, RWT_n and IEF_n values, is shown in Table A1 in the Appendix.

According to the data shown in Table 3.4, FWP in C&D, and manufacturing stages presents the highest values in Spain (3.03 and 3.89, respectively) while China presents the lowest values (0.60 and 0.68, respectively). Regarding the fuel extraction and processing stage, Italy presents the highest FWP value for agriculture,1.78, while Germany shows the lowest, 0.79. For mining, India presents the greater value, 3.47, and China presents the lowest, 1.02.

For the O&M stage, Equation (3.1) was used to calculate the FWP, using the data found for each company in a country. Table A2 in the Appendix shows the compilation of these values. Inflation corrections were applied as needed, and values are presented in Table A3 in the Appendix. The calculated FWP_n values for each country and weighted FWP_n for the O&M life cycle stage are shown in Table 3.5. Gas and oil technologies present the highest weighted FWP_n values (3.55 and 3.51, respectively) for the O&M stage. In contrast, solar PV technology presents the lowest value (1.32), followed by biomass-biogas (1.86). At a country level, India's coal O&M shows the highest FWP_n (8.14), followed by Brazil's hydropower O&M (5.69) and Japan's nuclear O&M (5.13). China's solar

PV O&M presents the lowest FWP_n (0.92), followed closely by Japan's oil and gas O&M (0.97), and USA's solar PV O&M (1.52).

Table 3.4. Fair wage potential in different life cycle stages for the analysed countries

Country	Construction & Decommissioning	Manufacturing	Fuel extraction and processing	
			Agriculture	Mining
Germany	1.64	2.09	0.79	-
Brazil	0.76	1.46	-	-
China	0.60	0.68	-	1.02
Spain	3.03	3.89	-	-
USA	2.53	1.93	1.17	2.21
France	1.87	2.16	-	2.11
India	1.71	2.91	-	3.47
Italy	2.38	2.81	1.78	-
Japan	1.50	1.46	-	1.44
UK	2.23	2.33	1.55	-
Russia	0.94	0.81	-	1.68

Table 3.5. Fair wage potential of the O&M stages for the analysed technologies

Power Technology	Country	Rate of workstation/ installed capacity	O&M's FWP_n	O&M's weighted FWP_n
Solar (International Renewable Energy Agency (IRENA), 2020b)	China	59.0%	0.92	1.32
	Japan	8.4%	3.61	
	USA	8.3%	1.52	
	India	7.1%	1.71	
Hydro (International Renewable Energy Agency (IRENA), 2020b)	China	29.0%	3.03	3.49
	India	19.0%	2.91	
	Brazil	11.0%	5.69	
Wind (Pitteloud, 2021)	China	36.4%	2.95	2.65
	USA	16.2%	2.42	
	Germany	9.4%	2.46	
	India	5.8%	1.94	
	Spain	4.0%	2.28	
	UK	3.6%	2.67	

Oil (International Energy Agency, 2019) [1]	China	28.2%	4.28	3.51
	USA	16.2%	2.60	
	India	7.4%	3.48	
	Japan	4.9%	0.97	
	Russia	4.2%	4.94	
Gas (International Energy Agency, 2019) [1]	China	28.2%	4.28	3.55
	USA	16.2%	2.74	
	India	7.4%	3.48	
	Japan	4.9%	0.97	
	Russia	4.2%	4.94	
Hard coal (Carbon Brief, 2020) [1]	China	50.1%	2.55	3.42
	USA	13.2%	2.65	
	India	11.4%	8.14	
Nuclear (International Energy Agency, 2019) [1]	USA	25.0%	3.24	3.04
	France	16.1%	1.71	
	China	11.6%	3.00	
	Japan	8.1%	5.13	
Biomass-biogas (IRENA, 2020b)	Germany	36.4%	1.74	1.86
	USA	12.2%	1.88	
	UK	9.2%	1.88	
	Italy	8.1%	2.34	

[1] installed capacity values used

3.3.2. Employment

Using the employment factors (EFi) for the selected power technologies presented in Table 3.3, the data from Table 3.2, the functional unit, and applying Equation (3.2), the employment results are depicted in Figure 3.2. The complete data is presented in Table A4 in the Appendix. The results suggest biomass provides the highest employment, equivalent to 1118 jobs-years/TWh. The second-best option is run-of-river with 734 jobs-years/TWh, followed by solar PV at 659 jobs-years/TWh. For this indicator, the reservoir provides the lowest life-cycle employment (41 jobs-years/TWh), possibly due to its relatively high efficiency (see Table 3.2) and lower labour requirements per unit of electrical output. With the results presented in Figure 3.2, it is possible to estimate the percentage of work positions for different electricity technologies in each life cycle stage (Table 3.6).

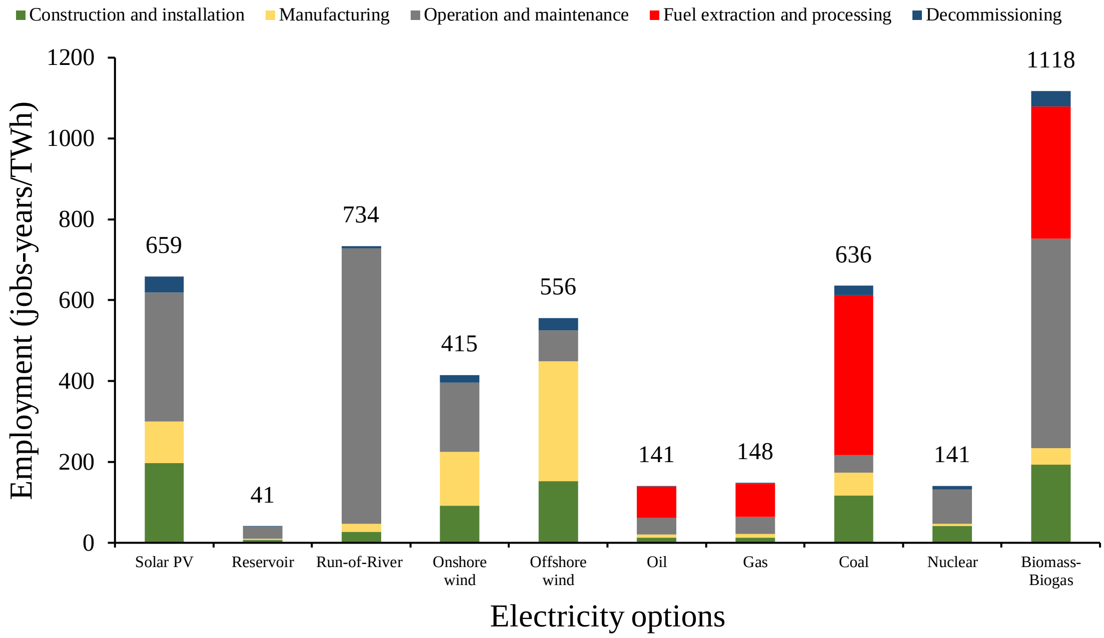

Figure 3.2. Employment provided by different electricity options.

Table 3.6. Percentage of work positions in each life cycle stage for different electricity technologies

Power technology	Percentage of work positions				
	Construction & installation	Manufacturing	O&M	Fuel extraction & processing	Decommissioning
Solar PV	30.0%	15.5%	48.5%	NA	6.0%
Hydro (Reservoir)	17.5%	8.3%	70.8%	NA	3.5%
Hydro (R-o-R)	3.7%	2.6%	92.9%	NA	0.7%
Onshore wind	22.0%	32.3%	41.3%	NA	4.4%
Offshore wind	27.4%	53.4%	13.7%	NA	5.5%
Oil	8.8%	6.3%	28.3%	54.9%	1.8%
Gas	8.8%	6.3%	28.3%	54.9%	1.8%
Coal	18.4%	8.9%	6.9%	62.2%	3.7%
Nuclear	29.7%	3.3%	60.4%	0.7%	5.9%
Biomass-biogas	17.3%	3.6%	46.4%	29.2%	3.5%

As outlined in Table 3.6, the O&M stage presents the highest percentage of work positions for run-of-river (92.9%), reservoir (70.8%), nuclear (60.4%), solar PV (48.5%), biomass-biogas (46.4%), and onshore wind (41.3%), showing the importance of this life cycle stage on the employment for the analysed technologies. Manufacturing emerges as a significant employment stage for offshore wind (53.4%), while the fuel extraction and processing stage presents the highest percentage of work positions for coal (62.2%), oil and gas (both with 54.9%).

3.3.3. Employment-Weighted Fair Wage Potential

The E-WFWP results for each option were estimated using Table 3.4, Table 3.5, Table 3.6, and Equation (3.3) and are displayed in Figure 3.3. The results indicate that run-of-river has the fairest wage potential option (3.33). Reservoir is ranked second best (2.80), followed by nuclear (2.56) and gas (2.17), the latter followed closely by oil (2.16). Solar PV technology presents the lowest E-WFWP value (1.16) but is still above the considered fair wage line. The relatively low value found for solar PV can be explained by the significant contribution of China's work positions on the weighting process (59%), with C&D, manufacturing, and O&M FWPs of 0.60, 0.68 and 0.92, respectively. Hydropower technologies also presented a low C&D FWP (0.99) due to China's C&D FWP (0.60) and Brazil's C&D FWP (0.76). However, the E-WFWPs were the highest, mainly because of the high FWP values of the O&M stage (3.49) and high work position rates: 92.9% for run-of-river and 70.8% for reservoir (see Table 3.6).

The results suggest, within the assumed premises, that the run-of-river option provides a higher social benefit concerning fair wages in the electricity generation sector. Considering the life cycle stages analysed, run-of-river could generate more positive social impacts than the other power technologies because, besides being the second most employing option (see Figure 3.2), the workers of the involved sectors, especially the O&M stage, have high incomes. The wage level of an individual or a family directly relates to the living situation and nutritional status, which can be linked with life expectancy, and thus to human health and social well-being (Vitorio Junior & Kripka, 2020). In the company scope, according to the United Nations (2023), beyond fulfilling a duty of care, ensuring the payment of decent wages to workers can be translated into an investment in human capital, bringing returns, such as a reduction of absenteeism and an increase of retention and motivation.

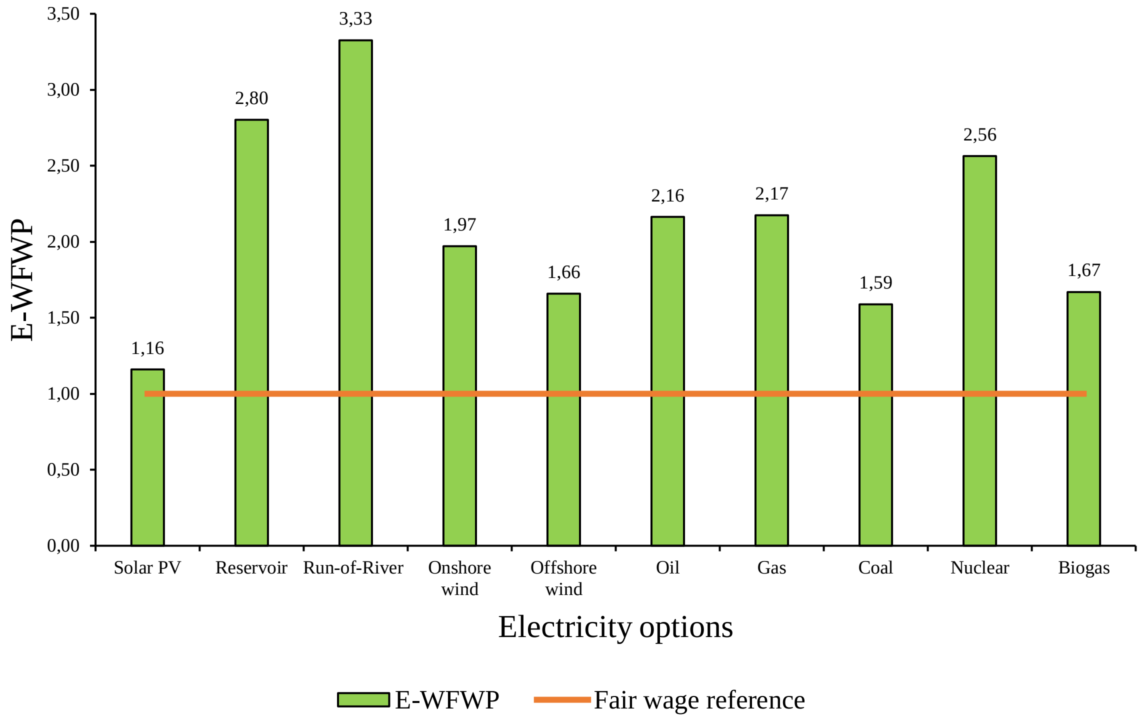

Figure 3.3. Employment-Weighted Fair Wage Potential of the different electricity options

The results presented in the S-LCA, considering the impact subcategory within the stakeholder category under concern, support the selection of the electricity options with the best potential social impacts, promoting the sustainability of the power sector. Through E-WFWP, decision-makers can choose among electricity generation options considering the potential upgrades to the worker's category. The results indicate the potential use of the indicator E-WFWP as a useful tool for assessing the social benefits of power technologies besides being potentially applicable to other industries. It is worth mentioning that the reference wage of the sector/region/country significantly influences the results of a fair or unfair wage.

3.4. Conclusions of Chapter 03

This paper originally proposes an employment-weighted fair wage assessment that aims to identify and implement socially sustainable electricity generation options. Recognizing the close relationship between fair salaries and SDGs 1 and 8, the study focuses on the power sector and adopts a life cycle approach to evaluate the fair wage potential of ten power technologies.

At a life cycle stage level, the findings for each stage are the following:

- C&D and manufacturing: Spain presents the highest FWP values (3.03 and 3.89, respectively), and China presents the lowest (0.60 and 0.68, respectively).

- Fuel extraction and processing:
  - Agriculture: Italy has the highest FWP value for agriculture (1.78), while Germany has the lowest (0.79).
  - Mining: India presents the greatest value (3.47), and China the lowest (1.02).
- O&M:
  - Gas and oil options present the highest weighted FWP_n values (3.55 and 3.51, respectively), while solar PV technology presents the lowest value (1.32), followed by biomass-biogas (1.86).
  - At a country level, India's coal O&M shows the highest FWP_n (8.14), followed by Brazil's hydropower O&M (5.69). China's solar PV O&M presents the lowest FWP_n (0.92), followed closely by Japan's oil and gas O&M (0.97).

The study's outcomes on employment assessment reveal that biomass-biogas is the option with the highest employment potential, presenting 1118 jobs-years/TWh. R-o-R ranks second with 734 jobs-years/TWh, and solar PV follows closely with 659 jobs-years/TWh. On the other hand, reservoir-based power generation is identified as the least favorable option in terms of employment, with only 41 jobs-years/TWh.

Based on the results of this work, hydro options emerge as the fairest wage potential options presenting values around three times greater than the target (3.33 for R-o-R, and 2.80 for reservoir), followed by nuclear (2.56). Solar PV technology presents the lowest E-WFWP value (1.16) but is still above the fair wage line.

According to the findings of this study, it is possible to realize that the method described in this paper incorporates the social dimension into the assessment of power options' sustainability and can also be adapted to different industries and countries, which has particular significance from a community standpoint. By considering an additional social aspect when implementing new power plants, this approach can enhance power sector policies. The E-WFWP sets itself apart from existing social sustainability indicators by linking the electricity generated by power options to social data, allowing decision-makers to move beyond technical and environmental issues.

However, there are certain limitations to the method. One drawback is the challenge of obtaining sector-specific primary data such as working hours and real wages, especially if the companies being analysed do not publish annual reports. Additionally, minimum living wage and real wage values used in the assessment need to be updated annually. Finally, it is important to note that this study did not consider unjustifiably high wages, such as managerial salaries, which warrants further discussion. Future research should expand the methodology to other stages of the power sector, such as transmission and distribution systems, as well as explore its applicability to other industries. Another issue that should be addressed is the capacity of powerful companies (ex: from oil and gas industry) to intentionally increase their employees' wages to impact the public perception as more socially sustainable than competitive low workforce power technologies.

3.5. Nomenclature

C	installed capacity	[MW]
CWT	contracted working time	[hours/week]
d	duration of employment	[years]
EF	employment factor	[jobs-year/MW]
E	employment provision	[jobs-year/TWh]
E-WFWP	employment-weighted fair wage potential	[FW_{eq}]
FWP	fair wage potential	[FW_{eq}]
IEF	inequality factor	[%]
MLW	minimum living wage	[(€/month]
P	amount of energy generated	[TWh]
RW	real (average) wage	[(€/month]
RWT	real working time	[hours/week]
TE	total employment of an energy technology	[jobs-year/TWh]

Subscripts and superscripts

i	*i*-th life cycle stage
J	total number of life cycle stages
n	process n
t	of an energy technology
tot	total

Abbreviations

C&D	Construction & Decommissioning
E-LCA	Environmental Life Cycle Assessment
E-WFWP	Employment-Weighted Fair Wage Potential
FU	Functional Unit
FWP	Fair Wage Potential
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCSA	Life Cycle Sustainability Assessment
O&M	Operation & Maintenance
PV	Photovoltaic
R-o-R	Run-Of-River
SDG	Sustainable Development Goal
S-LCA	Social Life Cycle Assessment
TU	Technischen Universität

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4. A life cycle framework for comparative analysis of power generation technologies based on prioritized Sustainable Development Goals

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Abstract

The ongoing energy transition in the power sector is vital for supporting global initiatives to mitigate climate change and foster sustainable development. This study addresses the challenge of aligning corporate power generation choices with prioritized sustainability goals by developing a comprehensive decision-support framework. This study tackles the challenge of aligning corporate power generation decisions with prioritized sustainability goals by establishing a comprehensive decision-support framework. The central hypothesis is that a framework incorporating environmental, social, and technical criteria can effectively guide the selection of power technologies based on life cycle assessment principles. The study applies a multicriteria decision analysis method to evaluate ten power generation options for twelve companies across three sectors: oil and gas, technology, and food and beverage. The findings reveal that run-of-river hydropower is the most balanced option, excelling in social, technical, and environmental dimensions. Meanwhile, solar photovoltaic and reservoir technologies perform particularly well concerning specific sustainable development goals. The results imply that companies can optimize their sustainability impact by aligning their power procurement strategies with this framework, promoting decarbonization and enhancing social equity. The conclusions underscore the proposed approach's utility for companies and policymakers in making informed, sustainable energy decisions.

Keywords: Sustainable electricity, Power generation technologies; Life Cycle Assessment; Sustainable Development Goals; Electricity generation; Social life cycle assessment.

Supplementary Materials

Supplementary Materials for this chapter are found in Appendix C.

Nomenclature

AWARE	Available WAter REmaining
DCB	Dichlorobenzene
E_i	Number of employment in life cycle stage i (jobs-year/TWh)
E-LCA	Environmental Life Cycle Assessment

eq	Equivalent
EROI	Energy Return on Investment
ESG	Environmental, Social, and Governance
E-WFWP	Employment-Weighted Fair Wage Potential
Fem_{tc}	percentage of female workforce in the analyzed power companies, related to the studied power technology, in the investigated country (%)
FemWF	Female workforce of a specific power technology (%)
FU	Functional Unit
GE_t	gender equality indicator of a power technology (%)
GWP	Global Warming Potential
GWP100	Global Warming Potential over 100 years
i	Life cycle stage
I	The total number of decision criteria (sustainability indicators or aspects)
IC	proportional installed capacity of the investigated country, regarding the Power technology (%)
IEA	International Energy Agency
I_i	Number of injuries in cycle stage *i* per 100,000 workers
ILO	International Labor Organization
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
J	Total number of life cycle stages
Jc	Total number of analyzed countries for a specific power technology
kWh	Kilowatt-hour
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LCSA	Life Cycle Sustainability Assessment
LPST	Lost Potential Service Time
m^3	Cubic meter
MAVT	Multi-Attribute Value Theory
MCDA	Multi-Criteria Decision Analysis
MGO	Microgrid Generation Option
MW	Megawatt
NMVOC	Non methane volatile organic compounds
O&G	Oil & Gas
O&M	Operation & Maintenance

OA	Total occupational accidents along the life cycle of an energy technology (Injuries/kWh)
PDF.m2.yr	Potentially Disappeared Fraction per square meter per year
PM	Particulate Matter
PPA	Power Purchase Agreements
PSLglo	Potential Species Loss from Land Use – Global
PV	Photovoltaic
R_{*j}	Worst value achieved by the j^{th} indicator of sustainability (anti-ideal value)
R_{ij}	Outcome achieved by the i^{th} system when is evaluated according to the j^{th} indicator
$\bar{R}_{ij}$	Normalized value achieved by the i^{th} system with respect to the j^{th} indicator of sustainability
R_j*	Optimum value of the j^{th} indicator of sustainability (ideal value)
R-o-R	Run-of-river
RoW	Rest of the World
SDG	Sustainable Development Goal
S-LCA	Social Life Cycle Assessment
TWh	Terawatt-hour
UBP	Environmental impact points
$v(a)$	Overall sustainability score of electricity option *a*
$v_i(a)$	score reflecting the performance of option *a* in criterion *i* (sustainability indicator or aspect)
w_i	Weight of importance for decision criterion *I* (sustainability dimension)
y	Year
ADR	Average dissipation rate
MJ	Megajoule

4.1. Introduction

The Sustainable Development Goals (SDGs) are part of the 2030 Agenda for Sustainable Development. SDGs are a universal call to end poverty, protect the environment and climate, and ensure that people everywhere can enjoy peace and prosperity (United Nations, 2018). In this sense, they are a deployment of the concept of sustainable development. The energy sector is a driver of social welfare (Martín-Gamboa et al., 2022) and access to electricity can propel economic and social development by boosting productivity and emerging new job-generating enterprises (Pueyo & Maestre, 2019). In the context of the ongoing energy transition (Lassio et al., 2021), the power sector plays a pivotal role in several SDGs. For instance, SDG #13 (Climate action) demands technologies with low carbon emissions such as renewable energy, fuel switching, efficiency gains, nuclear power, and carbon capture storage and utilization (Fawzy et al., 2020). Besides reducing the carbon intensity, energy security must be assured (Y. Zhang et al., 2021). As more low-carbon electricity becomes available, powering more process industry operations with electricity becomes a decarbonization strategy (Masuku et al., 2024). Also integrating smart grids, blockchain, and the Internet of Things can optimize energy efficiency, resilience, and accessibility Çelik et al. (2022). Industry electrification imposes an increased demand for utility-scale low-carbon energy, which demands expansion of electricity transmission and distribution networks (Wei et al., 2019).

The prevalent use of fossil fuels and the growth in energy demand challenge the target of mitigating climate changes in the electricity sector. The transition towards a low-carbon energy-efficient society is being promoted especially by SDG #7 (Affordable and clean energy), SDG #12 (Responsible consumption and production), and SDG #13 (Backes et al., 2021). According to the International Energy Agency (IEA) the future electricity supply is currently oriented by SDG #3.9 (air quality), SDG #7, and SDG #13 (Lassio et al., 2021). While the current priority is on SDG #7, choosing among alternative technologies to supply low-carbon energy (either renewable, nuclear, or decarbonized-fossil energy) often faces trade-offs (Luderer et al., 2019), which affects energy sustainability – a qualification that goes beyond clean and affordable highlight. The energy transition, propelled by SDG #7 and SDG #13, often overlooks the potential side effects it exerts on other SDGs. Higher costs associated with commissioning renewable energy systems could hinder economic growth, impacting other SDGs like #1 (No poverty), #2 (Zero hunger), #3 (Good health and well-being), #8 (Decent work and economic growth), #9 (Industry, innovation, and infrastructure), and #11 (Sustainable cities and communities) (Boa Morte et al., 2023). Also, the need to balance conflicting geopolitical interests in addressing climate change must be emphasized (Araújo et al., 2024).

Explicitly and effectively incorporating the SDG framework into the energy sector is a substantial challenge in targeting efficient and sustainable production systems (Martín-Gamboa et al., 2020). It demands a Life Cycle Assessment (LCA) tool for compiling and evaluating material and energy inputs and outputs to assess its production system's potential environmental life cycle impacts (ISO, 2006a). The work of Aberilla et al. (2020), for example, relates directly to SDGs #6 (Clean water and sanitation), #7, and #11, as it presents an approach called "synergen", which integrates electricity generation, cooking heat and water supply, assessing environmental and economic sustainability in remote communities in the Philippines, based on LCA. Dutta et al. (2023) focus on optimizing decentralized hybrid energy systems using advanced machine-learning techniques for load forecasting, proposing an integrated methodology combining this former with techno-economic and LCA evaluations, primarily relating to SDGs #7, #9, and #13. Also, the work of Song et al. (2023) evaluates the potential of using agricultural residues for large-scale bioenergy production in China and its implications for sustainability, employing an LCA framework to quantify the energy, environmental, economic, and social impacts, providing insights for policymakers to optimize bioenergy development and align it with regional sustainability goals, related mainly with SDGs#1, #7, and #13.

The economic dimension of sustainability can be evaluated through Life Cycle Costing (LCC), considering the costs incurred during the lifetime of the product, work, or service: purchase price and associated costs, operating costs, and end-of-life costs or residual value (European Commission, 2023). The work of Babalola et al. (2022), for instance, addresses the development of a hybrid power generation system for remote communities in Nigeria, having two of its parameters: the total net present cost representing the LCC of the system; and the Levelized Cost of Energy (LCOE). The study is strictly related to Microgrid Generation Options (MGO) and SDGs #7, #11, #12, and #13. Although the LCOE can help decision-makers determine the cost-effectiveness and viability of different clean electricity generation technologies (Gomstyn & Jonker, 2024), a wide range of values are informed for each generation technology in the literature (e.g., Lazard, 2024), as costs are more vulnerable to specific geopolitical scenarios, comparatively to technology-grounded indicators (Gomstyn & Jonker, 2024). Additionally, different LCOE models use different variables and formulas (Gomstyn & Jonker, 2024), hindering its ability to discriminate assertively the technical performances of the evaluated technologies.

At last, Social Life Cycle Assessment (S-LCA) evaluates the social impacts of products and services throughout their life cycle, utilizing a combination of Environmental Life Cycle Assessment (E-LCA) and methods from social sciences (UNEP, 2020). Also, S-LCA can monitor progress in SDGs #1, #3, #4 (Quality education), #5 (Gender equality), #8, #10 (reduced inequalities) (Backes & Traverso, 2022), and #12 (Responsible consumption and production) (Martín-Gamboa et al., 2020).

Existing life-cycle-based methods, often used separately, can be integrated into a Life Cycle Sustainability Assessment (LCSA) to encompass all dimensions (environmental, economic, and social) with multiple integrated indicators – e.g., in a multiple criteria decision-making platform (Kalbar & Das, 2020). LCSA (UNEP/SETAC, 2011) aligns with the triple bottom line concept, which emphasizes the simultaneous pursuit of economic prosperity, environmental quality, and social equity, as proposed by Elkington (1998).

Although a need is recognized for a combined LCSA-SDG framework (Backes & Traverso, 2022), a consensual approach still needs to be established. For instance, Henzler et al. (2020) introduce a sustainability assessment method for urban surface innovations using an SDG-based approach, aiming to assess the potential sustainability impacts of innovations before implementation. Nawaz Khan and Ali Abbas Kazmi (2022) focus on developing a framework for optimizing renewable energy systems, mainly standalone hybrid microgrids, including LCC, to provide a reference pathway for SDGs as well as to government and private investors for decision-making and policy optimization. Hannouf et al. (2023) present a methodological framework to connect LCSA categories and SDGs based on a literature review, introducing a qualitative heuristic research method to analyze these connections. Wulf et al. (2018) discuss the application of SDGs as a guideline for selecting indicators in LCSA, illustrating how they align with SDGs' specific indicators case-studying electrolytic hydrogen production. The authors indicate differences between goal-based and indicator-based assessments in LCSA, highlighting the challenges of matching product-level sustainability indicators with broader SDG targets. Pollok et al. (2021) explore the growth and challenges of S-LCA in evaluating the social impacts of products and services and emphasizes that SDGs must be more present S-LCA and that the definition of SDG targets prevents such inclusion.

Tokede & Globa (2024) introduce a Life Cycle Sustainability Tracker for dynamically visualizing and tracking LCSA performance, integrating the sustainability dimensions aligned with SDGs, applied to the pipeline infrastructure projects in India. Souza et al. (2022) explore the implications of bioenergy, particularly electricity from sugarcane biomass in Brazil, using LCA methods, linking impact categories to SDGs assessment. The study compares the SDG impacts of sugarcane biomass electricity with other energy sources in the Brazilian electricity matrix. Wang et al. (2022), focus on creating a Power System Sustainability index to evaluate and compare the energy systems of European Union countries, considering three dimensions (social, economic, and environmental) and using specific local indicators to measure its performance.

While previous studies, such as those by Henzler et al. (2020) and Souza et al. (2022), intended to integrate SDGs into LCA methodologies, often focusing on specific regions or a limited set of environmental indicators, this study expands on these work's methodologies by incorporating a global perspective and integrating a broader range of social and technical indicators, making it applicable to corporations across multiple sectors. It amplifies its geographical scope to the global power sector and introduces new indicators, like 'Microgrid Generation Option' (MGO) and 'gender equality' quantified based on corporate and sectoral data. These indicators are not typically considered in traditional LCA approaches, but they represent a significant advancement in aligning corporate actions with sustainability outcomes. Also, while Hannouf et al. (2023) present a qualitative heuristic method to connect LCA categories to SDGs, the present framework quantifies these connections using a Multi-Criteria Decision Analysis (MCDA) approach, providing quantitative and actionable insights. Furthermore, it differs from the work of Wang et al. (2022) by including several environmental categories and evaluating power generation technologies in terms of their contributions to SDGs. With this novel scope, the work (i) proposes a decision-support framework to choose among electricity technologies constrained by the prioritized SDGs of a corporation or sector; (ii) quantifies the impacts of electricity generation options aligned with the SDGs; (iii) has its framework underpinned by a life cycle approach, integrating social, technical, and environmental aspects of sustainable development.

This paper introduces a novel decision-support framework that integrates SDGs directly into the LCA methodology, bridging the gap between global sustainability targets and corporate energy choices. Unlike existing frameworks, this approach does not treat SDGs as abstract, overarching goals but aligns them explicitly with environmental, social, and technical indicators tailored for power generation technologies. This integration provides a more practical and measurable pathway for stakeholders to make informed decisions aligned with prioritized SDGs.

The resulting framework aims to support the selection of a most suitable power generation technology to a company or sector, understanding that these large electricity consumers can align their energy procurement strategies with their sustainability goals by selecting energy providers through mechanisms like Power Purchase Agreements (PPAs), or deciding for self-supplying its energy demand (e.g., oil refineries). Through PPAs, energy sellers can secure a guaranteed revenue stream over the contract period, while buyers can meet targets related to renewable energy procurement (Kandpal et al., 2024). PPAs are also an excellent instrument to achieve sustainability goals by promoting a green economy (Tantau et al., 2024). It is worth noting that the build-out of renewable capacity exposes a new scenario where, at times, more power is generated than consumed, known as “free power”, with different technologies used. This oversupply of electricity from renewable generation faces the willingness-to-pay for various sectors (Kempenaer et al., 2024). In the context of PPAs and “free power” market, the proposed decision-support framework may assist such companies in choosing electricity sources that contribute to their prioritized SDGs, ensuring alignment with their environmental, social, and governance (ESG) objectives.

The work applies the proposed framework to companies across three sectors (Oil & Gas, Technology, and Food & Beverage) as a case study to exemplify and demonstrate its versatility and adaptability. This broad applicability sets the framework apart from previous studies focusing on narrower or region-specific contexts. Also, the relevance of the novelty is its potential to guide decarbonization investments holistically, beyond the simplistic qualifications of clean and affordable energy, contributing to a sustainable energy transition guided by prioritized SDGs.

Despite SDGs targeting nations or regions, the proposed framework aims to assess the impact of products or services at the corporate level. Innovatively, this work aims to support stakeholders in pursuing their focused SDGs in deciding on adequate power options for their businesses. Furthermore, companies that align their strategies with the SDGs better manage regulatory and reputational risks and build resilience against future shocks (WBCSD, 2021).

4.2. Methods

The investigation focuses on the leading power generation technologies in the context of the energy transition from fossil-based to renewables: solar photovoltaic (solar PV), large hydropower plants (reservoir), small hydropower plants (Run-of-River, R-o-R), onshore wind, offshore wind, oil, gas, coal, nuclear, and biogas, previously approached by Tourinho et al. (2023).

4.2.1. General premises

In this study, 1 kWh generated by a technology is the Functional Unit (FU). The scope of the analysis is cradle-to-grave of the installations. It encompasses the stages presented by Rutovitz et al. (2015), i.e., the power station construction and installation, manufacturing of parts, operation & maintenance (O&M), decommissioning, and fuel extraction and processing.

Table 4.1 presents part of the social life cycle inventory (LCI) background data, technical assumptions for each power technology alternative, power plant installed capacity, world installed capacity, and efficiencies adapted from Tourinho et al. (2023). The presented 'installed capacity' values are the theoretical capacities necessary for the power plant, considering the efficiencies presented in Table 4.1, to meet 1 TWh/year production. The data on the world installed capacity for each power technology is based on the world breakdown of the technologies by IEA (IEA, 2020), complemented for wind energy (Pitteloud, 2021) and other renewable power (IRENA, 2020). Further specifications of the technologies are presented in Table S1 in the supplementary material.

Differently from Backes & Traverso (2022), which found that no LCC indicator could be assignable to SDGs, the present work builds a life cycle sustainability assessment based on technical indicators scrutinizing the power technologies on three dimensions (environmental, social, and technological), each with a set of indicators.

It is important to note that the efficiency of renewable energy technologies, such as solar photovoltaic (PV) and wind power, varies significantly depending on the resource potential in different countries. For example, the efficiency of solar PV systems can be higher in regions with greater solar irradiance, such as the Middle East or North Africa, compared to regions with lower insolation, such as Northern Europe. Similarly, wind energy efficiency depends on the wind speeds and wind profiles of specific locations.

Table 4.1. Summary of life cycle inventory data and assumptions (Adapted from Tourinho et al. (2023).

Power options	Power plant premises			
	Lifetime	Capacity factor	Installed capacity	Breakdown of the world's installed capacity
Solar PV	30 years (IEA, 2018)	13 % (IRENA, 2023)	848.8 MW	China - 36.0%, USA - 10.7%, Japan - 9.5%, Germany - 7.6%, Italy - 3.1%, Australia - 2.5%, South Korea - 2.1%, Spain - 2.0%, RoW [1] - 26.7%
Hydro (Reservoirs)	150 years [2] (Hossain et al., 2019)	36 % (IHA, 2022)	316.2 MW	Brazil - 9.5%, USA - 7.3%, Canada - 7.0%, Russia - 4.4%, India - 4.0%, Norway - 2.9%, Turkey - 2.7%, Japan - 2.4%, France - 2.1%, RoW - 57.8%
Hydro (R-o-R)	80 years (Blume-Werry & Everts, 2022)	36 % (IHA, 2022)	316.2 MW	USA - 7.3%, Canada - 7.0%, Russia - 4.4%, India - 4.0%, Turkey - 2.7%, Japan - 2.4%, France - 2.1%, RoW - 70.1%
Onshore wind	20 years (Delaney et al., 2023)	25 % (IRENA, 2023)	453.6 MW	China - 46.4%, USA - 20.0%, Germany - 9.3%, India - 6.6%, RoW - 17.8%
Offshore wind	20 years (Delaney et al., 2023)	29 % (IRENA, 2023)	394.2 MW	UK - 30.2%, China - 26.2%, Germany - 22.5%, Netherlands - 7.3%, RoW - 13.8%
Oil	30 years (Akber et al., 2017a)	33.7 % (Database.Earth, n.d.; IEA, 2020a)	338.7 MW	China - 28.2%, USA - 16.2%, India - 7.4%, Japan - 4.9%, Russia - 4.2%, RoW - 39.0%
Gas	30 years (Kabayo et al., 2019)	40 % (IEA, 2020a, 2020b)	281.2 MW	China - 28.2%, USA - 16.2%, India - 7.4%, Japan - 4.9%, Russia - 4.2%, RoW - 39.0%
Coal	30 years (Johnson et al., 2015)	53 % (IEA, 2020a, 2020b)	215.0 MW	China - 50%, USA - 13%, India - 11%, RoW - 25%
Nuclear	40 years (Gibon & Hahn Menacho, 2023)	84 %(IAEA, 2024)	136.7 MW	USA - 25.0%, France - 16.1%, China - 11.6%, Japan - 8.1%, RoW - 39.2%
Biogas	25 years (Kumawat et al., 2024)	50 % (IRENA, 2023)	229.0 MW	Germany - 37%, USA - 11.4%, UK - 9.2%, Italy - 7.1%, Turkey - 3.7%, RoW - 31.6%

[1] RoW – Rest of the World; [2] 150 years for the structural part and 80 years for the turbines.

4.2.2. Indicators selection

This study bases the selection of indicators on their ability to capture the environmental, social, and technological dimensions of sustainability in the context of power generation technologies, while also aligning with the SDGs. The choice of the indicators followed a rigorous process, drawing from established literature, international standards, and industry best practices. It categorizes the indicators into three main dimensions: environmental, social, and technological, each containing a specific set of indicators designed to evaluate the sustainability of the selected power generation options.

The indicators' selection considers, although not limited to, the works of Souza et al. (2022), Henzler et al. (2020), and Backes & Traverso (2022). SDG' targets and indicators are selected based on sustainability reports of the leading corporations in the energy sector. Considering the absence of consensus on the most appropriate indicators (Martín-Gamboa et al., 2022), available and suitable LCA categories (in the case of E-LCA) or indicators (in the case of S-LCA) are chosen to correspond to these SDGs' targets.

For the environmental dimension, the indicators were selected based on their relevance to assessing the E-LCA of power generation technologies. The environmental indicators were selected to reflect critical environmental challenges such as climate change, resource depletion, and ecosystem degradation, and they are aligned with internationally recognized life cycle impact assessment (LCIA) methods, ensuring a comprehensive evaluation of the potential environmental impacts of each technology.

Regarding the social dimension, the focus is on indicators that capture the social impacts of power generation technologies in terms of their contribution to job creation, wages, occupational safety, and gender equality, addressing SDGs related to decent work (SDG #8), gender equality (SDG #5), and poverty reduction (SDG #1). These indicators are applied in a S-LCA methodology and derived from data provided by organizations such as the International Labour Organization (ILO) and corporate sustainability reports.

For the technological dimension, the focused indicators intended to reflect the performance and scalability of power generation technologies in different contexts. The text in the sequence provides details for each dimension evaluated.

4.2.3. Environmental dimension

The inventory source and the emission factors of inputs and outputs used in the study are from the ecoinvent database, version 3.9, calculated using SimaPro software version 9.5. The indicators applied are from impact categories of European, Global, and single-issue methods recognized or recommended by the scientific community or Life Cycle Initiative groups. Table 4.2 presents the Life Cycle Inventory Assessment (LCIA) methods used for this study and the selected impact categories.

Table 4.2. Environmental impact categories selected for the study

LCIA method	Impact categories	Unit
ReCiPe 2016 Midpoint (H) V1.08 / World (2010) H	Fine particulate matter formation	kg PM2.5 eq/kWh
	Terrestrial acidification	kg SO2 eq/kWh
	Freshwater eutrophication	kg P eq/kWh
	Marine eutrophication	kg N eq/kWh
	Terrestrial ecotoxicity	kg 1,4-DCB/kWh
	Freshwater ecotoxicity	kg 1,4-DCB/kWh
	Marine ecotoxicity	kg 1,4-DCB/kWh
	Human carcinogenic toxicity	kg 1,4-DCB/kWh
	Human non-carcinogenic toxicity	kg 1,4-DCB/kWh
	Land use	m2a crop eq/kWh
	Fossil resource scarcity	kg oil eq/kWh
	Mineral resource scarcity	kg Cu eq/kWh
Mineral resource dissipation (Charpentier Poncelet et al., 2022) V1.00	Lost potential service time (LPST)100	kg Fe-eq/kWh
	average dissipation rate (ADR)	kg Fe-eq/kWh
AWARE V1.05	Water use	m3/kWh
Cumulative Energy Demand V1.11 / Cumulative energy demand	Non-renewable, fossil	MJ/kWh
	Non-renewable, nuclear	MJ/kWh
	Non-renewable, biomass	MJ/kWh
EPD (2018) V1.04	Photochemical oxidation	kg NMVOC/kWh
Ecological Scarcity 2021 V1.01 / Ecological scarcity 2021, eiv3	Waste, non-radioactive	UBP/kWh
	Radioactive waste to deposit	UBP/kWh
EN 15804 +A2 (adapted) V1.00 / EF 3.1 normalization and weighting set	Resource use, minerals, and metals	kg Sb eq/kWh
IPCC 2021 GWP100 V1.02	GWP100 - fossil	kg CO2-eq/kWh
IMPACT World+ Endpoint V1.03 / IMPACT World+ (Stepwise 2006 values)	Marine acidification, short term	PDF.m2.yr/kWh
ReCiPe 2016 Endpoint (H) V1.08 / World (2010) H/A	Ecosystems	species.yr/kWh
Land use impacts on biodiversity (Chaudhary et al., 2015) V1.01	PSLglo Occupation	PDF.year/kWh
	PSLglo Transformation	PDF.year//kWh

PSL_{glo}: Potential Species Loss from Land Use – Global

The indicators' selection follows their relevance to assessing the environmental impacts of power generation technologies, as each indicator corresponds to a specific environmental concern. Some examples are:

- Climate change mitigation (via GWP100) is a critical priority for most countries and directly relates to SDG #13 (Climate Action).
- Air quality (via particulate matter formation and acidification) is essential for human health and aligns with SDG #3 (Good Health and Well-being).
- Water quality and availability (via eutrophication and water use) are key for maintaining ecosystems and human livelihoods, aligning with SDG #6 (Clean Water and Sanitation).
- Resource conservation (via fossil and mineral resource scarcity) supports sustainable consumption and production practices, contributing to SDG #12 (Responsible Consumption and Production).
- Biodiversity protection (via land use and ecotoxicity) ensures the preservation of natural ecosystems, which is critical to SDG #15 (Life on Land).

The environmental performance of power generation technologies depends significantly on geographic and national-specific factors, as different regions present unique environmental conditions, resource availability, and policy frameworks. For example, solar PV systems perform better in areas with high solar irradiance, such as the Middle East or North Africa (Paul Breeze, 2019), directly influencing key indicators like EROI. Coal-fired plants in countries with advanced pollution control technologies emit fewer pollutants (like particulate matter, sulfur dioxide, or mercury) than similar plants in countries without such technologies (Asif et al., 2022). The impact of power generation on biodiversity and land use also varies geographically. In regions with fragile ecosystems or high biodiversity, such as the Amazon or other tropical regions, the impact of land use from large infrastructure projects like hydropower can be much more pronounced (Palmeirim & Gibson, 2021). This makes land use and ecosystem indicators (e.g., Potential Species Loss from Land Use) more critical in such contexts, as compared to regions with less sensitive ecosystems.

Knowing that these variations can occur from country to country, the breakdown of the installed capacity of each technology, presented in Table 4.1, was considered in the impact allocation when selecting the process data in SimaPro. Therefore, Table S1 in the supplementary material presents the processes used in each technology.

4.2.4. Social dimension

The social dimension in LCA is a critical component in evaluating the impacts of power generation technologies on society. Therefore, specific indicators should be selected to represent the main social issues addressed by the SDGs.

S-LCA analysts need a greater consensus on the most appropriate indicators (Martín-Gamboa et al., 2022), which depends on the case being studied. The present work selects social indicators based on a previous literature search by the authors on S-LCA in the power sector (not in the scope of the present work), resulting in a set of indicators: (i) Total employment; (ii) Direct employment; (iii) Manufacturing employment rate; (iv) Employment-Weighted Fair Wage Potential (E-WFWP); (v) Occupational accidents (number of non-fatal occupational injuries); (vi) fatalities; and (vii) Gender equality. Indicators (i) to (iv) originate from previous work (Tourinho et al., 2023), while indicators (v) to (vii) are contributions from the present study.

Social indicators related to human harms are frequently cited, like carcinogenic and non-carcinogenic toxicity (Vogt Gwerder et al., 2019), human health damages (Volkart et al., 2016), and human toxicity potential (Galán-Martín et al., 2016). The social set of indicators of the present study does not include them because they are part of already established human health environmental indicators. The same principle applies to the indicator "land use/conflict" utilized by Cooper et al. (2018), Li et al. (2017), and Gallego Carrera and Mack (2010), among others. Special attention is due to indicators overlapping between S-LCA and E-LCA, especially for human health and resource use (Nubi et al., 2022b).

4.2.4.1. Calculation of occupational accidents

Some assumptions and frameworks apply to the utilization of occupational accidents (non-fatal occupational injuries) as parameters for the comparative social performance of power technologies. The data is from the International Labor Organization (ILO, 2024). The numbers are presented as non-fatal occupational injuries per 100,000 workers by economic activity and are reported in Table S2 in the supplementary material. The values presented for each of the technologies are proportional to the number of workers in each stage and derive from Equation 4.1.

$$OA = \sum_{i}^{J} \left(E_i \times \frac{I_i}{10^5} \right) \times 10^{-9} \quad \text{Eq. (4.1)}$$

where *OA* is the total occupational accidents along the life cycle of a given energy technology (Injuries/kWh); E_i is the number of employment in life cycle stage i (jobs-year/TWh); I_i is the number of injuries in cycle stage *i* per 100,000 workers; *J* is the total number of life cycle stages; and *i* is the life cycle stage.

Table 4.3 shows the data used for the E_i values adapted from previous work (Tourinho et al., 2023).

Table 4.3. Employment in different electricity generation options

Power Technology	Employment (jobs-years/TWh)					
	Construction & installation	Manufacturing	O&M	Fuel extraction & processing	Decommissioning	Total Employment
Solar PV	367.8	189.6	594.2	0.0	73.6	1225.1
Hydro (Reservoir)	15.6	7.4	63.2	0.0	3.1	89.3
Hydro (R-o-R)	62.4	43.1	1549.5	0.0	12.5	1667.5
Onshore wind	72.6	106.6	136.1	0.0	14.5	329.8
Offshore wind	157.7	307.5	78.8	0.0	31.5	575.5
Oil	14.7	10.5	47.4	91.9	2.9	167.4
Gas	12.18	8.72	39.36	76.26	2.44	138.96
Coal	80.3	38.7	30.1	271.9	16.1	437.0
Nuclear	40.3	4.4	82.0	1.0	8.1	135.9
Biomass-Biogas	128.2	26.6	343.5	215.9	25.6	739.9

4.2.4.2. Fatalities calculation

The number of fatalities for each power technology is from Our World in Data (2021), and comprises death rates from energy sources, measured as the number of deaths from air pollution and accidents per teraWatt-hour (TWh) of energy production.

4.2.4.3. Gender equality

Gender equality data is gathered for each power generation technology, whenever available, considering the percentage of female workforce. Whenever publications with global gender values for a given technology are unavailable, the present work uses the values for the leading countries in the specific technology, applying the world installed capacity of the technology, presented in Table 4.1. For these cases, power companies operating in each country, and responsible for the significant share of its electricity generation portfolio are selected and analyzed. The most recent reports of each company (annual, financial, consolidated, or corporate responsibility report) are employed to gather gender data. Tables S3-S5, in the supplementary material, present the share of female employees in each analyzed company/sector. The Gender equality indicator in the present work is the distance to a considered target, i.e., the distance to 50% of the female workforce (theoretical ideal scenario) and its calculation is according to Equation 4.2.

$$GE_t = |50\% - FemWF| \qquad \text{Eq. (4.2)}$$

where GE_t is the gender equality indicator of a power technology (%), and *FemWF* is the female workforce of a specific power technology (%). Whenever a worldwide *FemWF* value is not available, Equation 4.3 is applied.

$$FemWF = \sum_{i=1}^{Jc} Fem_{tc} \times IC \qquad \text{Eq. (4.3)}$$

where Fem_{tc} is the mean percentage of the female workforce in the analyzed power companies, related to the studied power technology, in the investigated country (%); *IC* is the proportional installed capacity of the investigated country, regarding the power technology (%), and *Jc* is the total number of analyzed countries for a specific power technology. The lower the value found for GE_t, the greater the gender equality.

4.2.5. Technological dimension

For the technological dimension, two categories assess the power options: the energy return on investment (EROI) (Hall et al., 2014) and the Microgrid Generation Option (MGO). A group of assumptions and frameworks are considered for utilizing the selected technological indicators as comparison parameters for assessing the technical performance of the power technologies.

4.2.5.1. Energy return on investment

The economic strength of a society depends heavily on two factors: how efficiently it can provide valuable work (or exergy) and how proficient it is at using it to produce goods and services (Weissbach et al., 2018). A fraction of the available usable work (or exergy) must be invested to provide it. Such net energy analysis is sometimes called the assessment of energy surplus, energy balance, or energy return on investment – EROI (Hall et al., 2014).

The EROI is a dimensionless ratio. It represents the amount of energy obtained (or returned) from an energy production process compared to the amount of energy invested to produce that energy. The present study considers EROI an indicator of the energy productivity of a power plant, and its relevancy is related to policies, such as the optimization of energy use in an industry and the promotion of a faster recovery of energy investment (Jain et al., 2020).

EROI is a measure of energy system viability, which indirectly covers long-term economic efficiency by reflecting the energy productivity of each technology, where high EROI typically translates into lower long-term costs due to more efficient energy use and lower operational expenses over the lifecycle. According to Fabre (2019), an inverse relationship between EROIs and energy prices is consistently found empirically, so a declining EROI could mean higher energy prices.

The EROI for a power generation technology is based on the values presented by Weißbach et al. (2013), Dale et al. (2012), Trainer (2018) and Jain et al. (2020); the average of these values are shown in Table 4.4, and are applied in the assessment.

Table 4.4. EROI dimensionless values for the power options

Power Technology	Weißbach et al. (2013)	Dale et al. (2012)	Trainer (2018)	Jain et al. (2020)	Mean value
Solar PV	1.6	9.0	10.0	7.0	6.9
Hydro	35.0	94.0	80.0	41.0	62.5
Wind	3.9	22.0	18.0	38.0	20.5
Oil	-	-	-	16.0	16.0
Gas	28.0	49.0	-	35.0	37.3
Coal	30.0	14.0	-	25.0	23.0
Nuclear	75.0	14.0	-	8.0	32.3
Biogas	3.5	13.0	13.0	4.0	8.4

4.2.5.2. Microgrid Generation Option

As a result of the extreme centralization of the utility grid, numerous important drawbacks such as existing network expansion, limitations on the integration of renewable energy sources, transmission line congestion, and monopoly of the utility grid demand alternative approaches besides the vertically integrated main grids. In this context, the need to provide power to remote communities, where the connection with the main grid is unachievable, demands diminutive autonomous grids. Such small-scale autonomous grids with distributed generations and a cluster of loads are called microgrids (Arunkumar et al., 2022).

To include indicators applicable to power technologies, especially related to SDGs #7 and #9, the work introduces the "Microgrid Generation Option" (MGO) to capture the importance of access to affordable energy in places with deficient infrastructure. It is a semi-quantitative category that indicates that technologies are more amenable to reaching remote places on a small scale. A given technology scores in this category if it can be applied in microgrids or isolated areas. Based on the literature, the following options are considered as scoring technologies: Gas (Lambert et al., 2006), Solar PV, Onshore Wind, Run-of-river hydro (Hirsch et al., 2018), and Biogas (Sarkar, 2021). In this category, these technologies score 1, while the others (Reservoir, Offshore wind, Oil, Coal, and Nuclear) achieve a null score.

It is worth noting that storage systems for stochastic renewable energy systems are not included in the framework, since storage requirements are often context-specific and difficult to generalize for every application, leading to additional uncertainty in the results. Furthermore, all the evaluated technologies based on renewable sources depend on storage capacity to face supply intermittence. In this scenario, adding this issue to the analysis would not contribute to the discriminatory ability of the present decision-support framework.

4.2.6. Normalization, aggregation, and performance score

To simplify and render decision-making more accessible, either a reduction of assessed indicators or their aggregation to an index is recommended (Buchmayr et al., 2022). In this scope and aiming at the most adequate technologies for each SDG, a Multicriteria Decision Analysis (MCDA) is proposed. The MCDA methods have been widely applied to energy systems to obtain an integrated decision-making result (Wang et al., 2009). A complete MCDA requires the following steps: 1) selection of technology options; 2) selection of criteria and indicators; 3) quantification of the indicators for each option; 4) normalization of indicators; 5) weighting of the indicators; 6) aggregation; and 7) ranking of alternatives (Volkart et al. (2016).

The quantification of the selected social, technical, and environmental indicators is conducted in the LCIA phase, followed by a normalization step based on the work of Díaz-Balteiro and Romero (2004). The methodology differs depending on the direct or indirect effect of a criterion on sustainability (if beneficial, the higher, the better, or, if deleterious, the lower, the better). Calculation of beneficial criteria – e.g., Direct employment, EROI, and E-WFWP – follows Equation 4.4. Deleterious criteria, such as Terrestrial acidification, Land use, and Global warming potential (GWP), are calculated with Equation 4.5. The normalization procedure produces dimensionless sustainability indicators bounded between 0 and 1, with the technology closer to the target receiving a score of 1, while the farthest from the target receives a score of zero, resulting in a normalized decision matrix of *n* rows (*i* = 1, ..., n^{th} system) and *m* columns (*j* = 1, …, m^{th} indicator).

$$\bar{R}_{ij} = 1 - \frac{R_j^* - R_{ij}}{R_j^* - R_{*j}} \quad \text{Eq. (4.4)}$$

$$\bar{R}_{ij} = 1 - \frac{R_{ij} - R_j^*}{R_{*j} - R_j^*} \quad \text{Eq. (4.5)}$$

where $\bar{R}_{ij}$ is the normalized value achieved by the i^{th} system with respect to the j^{th} indicator of sustainability; R_j^* is the optimum value of the j^{th} indicator of sustainability (ideal value) (maximum for Equation 4.4 and minimum for Equation 4.5); R_{*j} is the worst value achieved by the j^{th} indicator of sustainability (anti-ideal value); R_{ij} is the outcome achieved by the i^{th} system when is evaluated according to the j^{th} indicator.

All the criteria are given the same relevance to sustainability, meaning they are equally weighted (summing 100%). Normalized values are multiplied by each weight, yielding the weighted normalized decision matrix. The aggregation results from summing the weighted normalized performance values, obtaining a performance score for each power technology in each SDG.

4.2.7. Case Studies

The proposed decision-support framework is applied to companies with diverse SDGs' targets from different industries. Additionally, since stakeholders may prioritize different dimensions, an analysis incorporating various weightings is crucial. Multi-Criteria Decision Analysis (MCDA) is a valuable tool for such assessments, as it allows for evaluating results from multiple perspectives. MCDA methods are extensively applied to energy systems, leveraging multiple criteria to produce integrated decision-making outcomes (Wang et al., 2009), particularly when accounting for the inherent vagueness and ambiguity in human judgments (Ren, 2018).

In the present study, the multi-attribute value theory (MAVT) has been used to conduct the analysis, as this approach is recognized as one of the most intuitive methods within MCDA. MAVT's decision-aiding process involves listing the alternatives and evaluating them based on a common set of criteria. Each option is assigned scores according to its performance on these criteria. The criteria are then weighted to reflect their relative importance, and an overall score for each option is calculated by aggregating these weighted scores (Morton, 2018). In this method, the overall sustainability score for each alternative is estimated as follows (Azapagic & Perdan, 2005):

$$v(a) = \sum_{i=1}^{I} w_i v_i(a) \qquad \text{(Eq.4.6)}$$

where $v(a)$ is the overall sustainability score of electricity option a; w_i weight of importance for decision criterion I (sustainability dimension); $v_i(a)$ is the score reflecting the performance of option a in criterion i (sustainability indicator or aspect); I is the total number of decision criteria (sustainability indicators or aspects).

MCDA is conducted in two stages. First, scores for each dimension (environmental, technical, and social) are calculated using Equation (4.6) based on the corresponding sustainability indicators and their weights. Here, the decision criteria represent the sustainability indicators. In the second stage, the decision criteria are the dimensions, and Equation (4.6) is applied to estimate the overall sustainability score using the previously obtained scores and weights.

4.3. Results and Discussion

The information regarding SDGs' targets, indicators, and impact categories references are presented in Table S6 in the supplementary material. Table 4.5 displays selected social, technical, and environmental categories/indicators for the proposed framework. It is worth noting that the 'Non-renewable energy' category is the mean of three impact categories: Non-renewable, fossil, nuclear, and biomass presented in the LCIA Method 'Cumulative Energy Demand' while the category 'Potential Species Loss from Land Use – Global (PSL_{glo})' is the mean of two impact categories described in Chaudhary et al. (2015): PSL_{glo} Occupation and PSL_{glo} Transformation.

The selected indicators are calculated for each power technology based on the installed capacities presented in Table 4.1, using Equations 4.1, 4.2, and 4.3, and information compiled from literature. The results are presented in Table S7 in the supplementary material. Then, the application of Equations 4.4 and 4.5 produces the normalized matrix of the social, technical, and environmental impacts' values, shown in Table 4.6. A statistical analysis is conducted, highlighting power options with normalized values exceeding or falling below one standard deviation, as presented in Table S8 of the supplementary material. The results indicate that solar PV technology emerges as a superior option for the categories Direct and Total Employment, "Gender Equality" and "PSL_{glo} Transformation". Hydropower options demonstrate strong performance in the categories "E-WFWP," "EROI," "Mineral Resource Scarcity," "Lost Potential Service Time (LPST)," and "Non-Renewable Biomass" (Non-renewable energy). Specifically, reservoir hydropower shows favorable outcomes in "Occupational Accidents," while "Run-of-River (R-o-R)" outstands in Direct and Total Employment. Additionally, wind power performs well in "Manufacturing employment rate". The nuclear option exhibits good performance in the categories "Lost Potential Service Time (LPST)" and "Non-Renewable Biomass". Conversely, coal, oil, and solar PV are identified as having the most statistically significant negative scores in 16, 14, and 12 categories, respectively.

The normalized performance of the evaluated power technologies in each dimension (social, technical, and environmental) and the respective mean values are displayed in Figure 4.1.

Table 4.5. Selected indicators for the proposed framework

SDG	Impact categories/indicators	Unit
SDG 1: No poverty	Total employment	jobs-y/kWh
	E-WFWP	-
SDG 2: Zero Hunger	Terrestrial acidification	kg SO_2 eq/kWh
	Terrestrial ecotoxicity	kg 1,4-DCB/kWh
	Land use	m^2a crop eq/kWh
SDG 3: Good Health and Well-Being	Human carcinogenic toxicity	kg 1,4-DCB/kWh
	Human non-carcinogenic toxicity	kg 1,4-DCB/kWh
	Fine particulate matter formation	kg PM2.5 eq/kWh
	Fatalities	Fatalities/kWh
SDG 5: Gender equality	Gender equality	%
SDG 6: Clean Water and Sanitation	Freshwater ecotoxicity	kg 1,4-DCB/kWh
	Freshwater eutrophication	kg P eq/kWh
	Water use	m^3/kWh
SDG 7: Affordable and Clean Energy	Microgrid Generation Option (MGO)	-
	Non-renewable energy (MJ)	MJ/kWh
	Fossil resource scarcity	kg oil eq/kWh
	Energy return on investment (EROI)	-
SDG 8: Decent work and economic growth	Direct Employment	jobs-y /kWh
	Total Employment	jobs-y /kWh
	E-WFWP	-
	Occupational accidents	Injuries/kWh
	Fatalities	Fatalities/kWh
SDG 9: Industry, innovation and infrastructure	Microgrid Generation Option (MGO)	-
	Manufacturing employment rate	%
	Average Dissipation Rate (ADR)	kg Fe-eq/kWh
	Lost Potential Service Time (LPST)	kg Fe-eq/kWh
	Mineral resource scarcity	kg Cu eq/kWh
	Fossil resource scarcity	kg oil eq/kWh
SDG 10: Reduced inequalities	E-WFWP	-
SDG 11: Sustainable Cities and Communities	Fine particulate matter formation	kg PM2.5 eq/kWh
	Photochemical oxidation	kg NMVOC/kWh
	Waste, non-radioactive	UBP/kWh
	Radioactive waste to deposit	UBP/kWh

SDG 12: Responsible Consumption and Production	Resource use, minerals, and metals	kg Sb eq/kWh
	Mineral resource scarcity	kg Cu eq/kWh
	Average Dissipation Rate (ADR)	kg Fe-eq/kWh
	Lost Potential Service Time (LPST)	kg Fe-eq/kWh
	Radioactive waste to deposit	UBP/kWh
	Waste, non-radioactive	UBP/kWh
SDG 13: Climate Action	Climate change (GWP100 - fossil)	kg CO_2-eq/kWh
SDG 14: Life Below Water	Marine eutrophication	kg N eq/kWh
	Marine ecotoxicity	kg 1,4-DCB/kWh
	Marine acidification, short term	PDF.m^2.y/kWh
SDG 15: Life on Land	Ecosystems	species.y/kWh
	Potential Species Loss from Land Use (PSL) - Global	PDF.y /kWh
	Land use	m^2a crop eq/kWh
	Terrestrial acidification	kg SO_2 eq/kWh
	Terrestrial ecotoxicity	kg 1,4-DCB/kWh
SDG 16: Peace, Justice, and Strong Institutions	Gender equality	%

Table 4.6. Results of the normalized matrix of the power technologies

Impact categories / indicators	Solar PV	Reservoir	R-o-R	Wind - onshore	Wind - offshore	Oil	Gas	Coal	Nuclear	Biogas
Direct employment	0.63	0.02	1.00	0.11	0.14	0.01	0.00	0.05	0.05	0.28
Manufacturing employment rate	0.25	0.11	0.00	0.58	1.00	0.07	0.07	0.12	0.01	0.02
Total employment	0.72	0.00	1.00	0.15	0.31	0.05	0.03	0.22	0.03	0.41
Occupational accidents	0.00	1.00	0.47	0.74	0.45	0.94	0.96	0.70	0.94	0.44
Fatalities	1.00	0.95	0.95	1.00	1.00	0.25	0.89	0.00	1.00	0.81
Gender equality	1.00	0.53	0.53	0.40	0.40	0.44	0.44	0.00	0.53	0.43
W-EFWP	0.00	0.76	1.00	0.38	0.23	0.46	0.47	0.20	0.65	0.23
Energy return on investment (EROI)	0.11	1.00	1.00	0.33	0.33	0.26	0.60	0.37	0.52	0.13
Microgrid Generation Option (MGO)	1.00	0.00	1.00	1.00	0.00	0.00	1.00	0.00	0.00	1.00
Fine particulate matter formation	0.93	1.00	1.00	0.99	0.99	0.09	0.97	0.00	0.99	0.86
Terrestrial acidification	0.95	1.00	1.00	0.99	0.99	0.00	0.97	0.16	1.00	0.80
Freshwater eutrophication	0.89	1.00	1.00	0.98	0.98	0.96	0.98	0.00	0.99	0.89
Marine eutrophication	0.85	1.00	1.00	0.96	0.95	0.28	0.97	0.00	0.49	0.88
Terrestrial ecotoxicity	0.49	1.00	1.00	0.94	0.93	0.00	0.98	0.85	0.94	0.93
Freshwater ecotoxicity	0.00	1.00	1.00	0.52	0.75	0.85	0.95	0.16	0.95	0.78
Marine ecotoxicity	0.00	1.00	1.00	0.55	0.76	0.72	0.95	0.11	0.94	0.78
Human carcinogenic toxicity	0.69	1.00	1.00	0.69	0.74	0.77	0.88	0.00	0.97	0.87
Human non-carcinogenic toxicity	0.71	1.00	1.00	0.94	0.94	0.86	0.98	0.00	0.88	0.85
Land use	0.00	0.82	1.00	0.96	1.00	0.81	0.93	0.58	1.00	0.71
Fossil resource scarcity	0.93	1.00	1.00	0.99	0.99	0.00	0.32	0.16	1.00	0.92
Mineral resource scarcity	0.00	0.99	1.00	0.47	0.48	0.65	0.77	0.77	0.37	0.73
Lost potential service time (LPST)100	0.43	1.00	0.98	0.58	0.69	0.00	0.30	0.73	1.00	0.84

average dissipation rate (ADR)	0.90	1.00	1.00	0.95	0.96	0.00	0.33	0.95	1.00	0.96
Water use	0.92	0.00	1.00	1.00	0.99	0.93	0.99	0.93	0.90	0.99
Non-renewable, fossil	0.93	1.00	1.00	0.99	0.99	0.00	0.33	0.15	1.00	0.92
Non-renewable, nuclear	0.99	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.00	1.00
Non-renewable, biomass	0.26	0.97	0.98	0.80	0.82	0.53	0.63	0.41	1.00	0.00
Photochemical oxidation	0.94	1.00	1.00	0.99	0.99	0.00	0.80	0.32	1.00	0.86
Waste, non-radioactive	0.00	1.00	1.00	0.81	0.91	0.09	0.45	0.90	0.98	0.82
Radioactive waste to deposit	0.99	1.00	1.00	1.00	1.00	0.99	1.00	1.00	0.00	0.99
Resource use, minerals and metals	0.00	1.00	1.00	0.84	0.83	0.94	0.97	0.94	0.97	0.89
GWP100 - fossil	0.93	1.00	1.00	0.99	0.99	0.05	0.54	0.00	1.00	0.89
Marine acidification, short term	0.93	0.98	1.00	0.99	0.99	0.03	0.54	0.00	1.00	0.90
Ecosystems	0.87	0.91	1.00	0.98	0.99	0.02	0.69	0.00	0.99	0.78
PSLglo Occupation	0.00	1.00	1.00	0.96	0.99	0.93	0.99	0.56	1.00	0.70
PSLglo Transformation	1.00	0.00	0.25	0.28	0.27	0.37	0.31	0.28	0.27	0.31

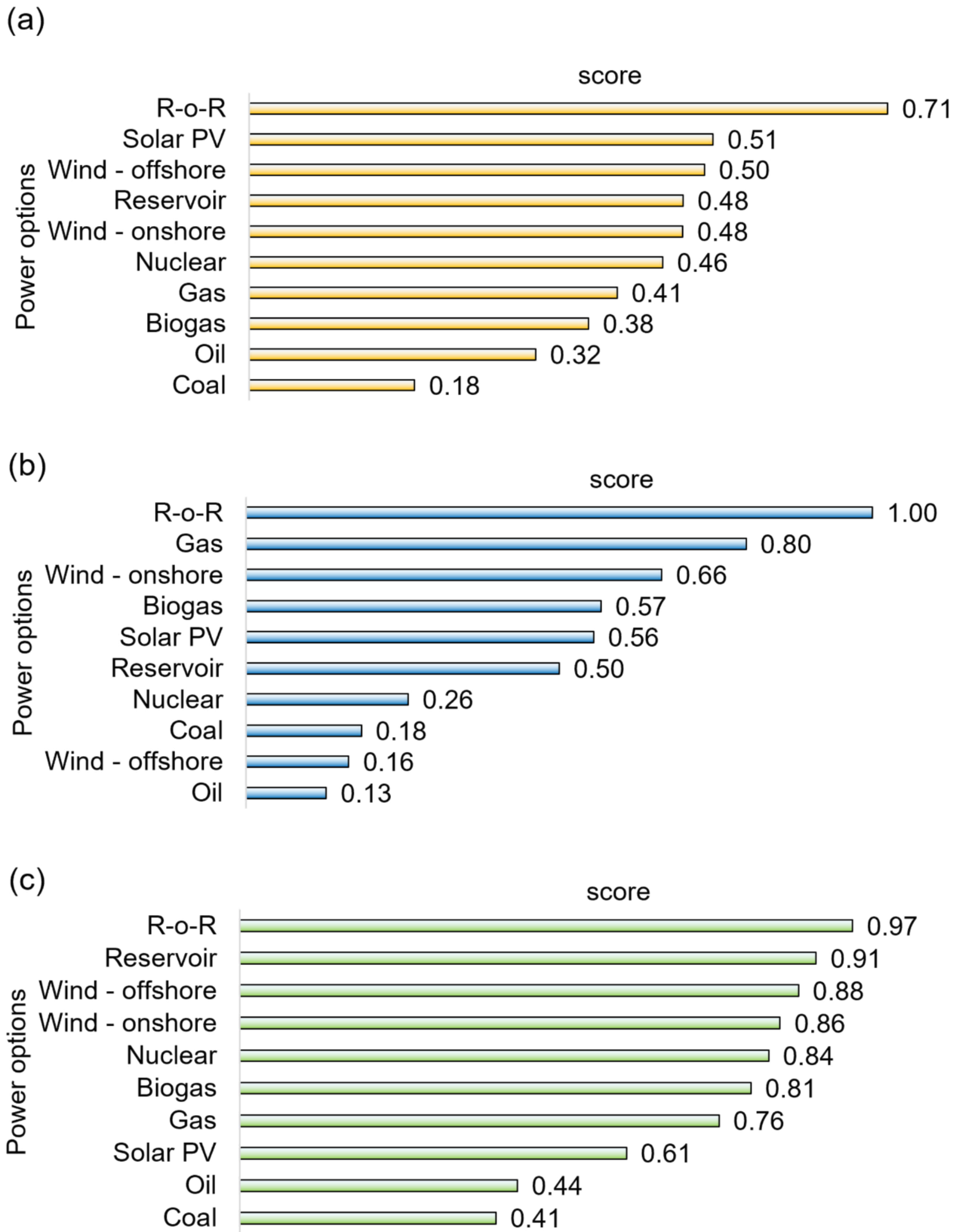


Figure 4.1 Ranking of power options considering the related scores for the three dimensions: (a) Social, (b) technical, and (c) environmental.

Figure 4.1a shows the S-LCA results, where R-o-R is the best option in the social dimension. Its performance is boosted by the categories “E-WFWP”, “direct employment”, and “total employment”. On the other hand, the low scores presented by coal and oil can be attributed to poor performance in most of the indicators, but especially in “Direct Employment”, “Fatalities”, and “Gender Equality”.

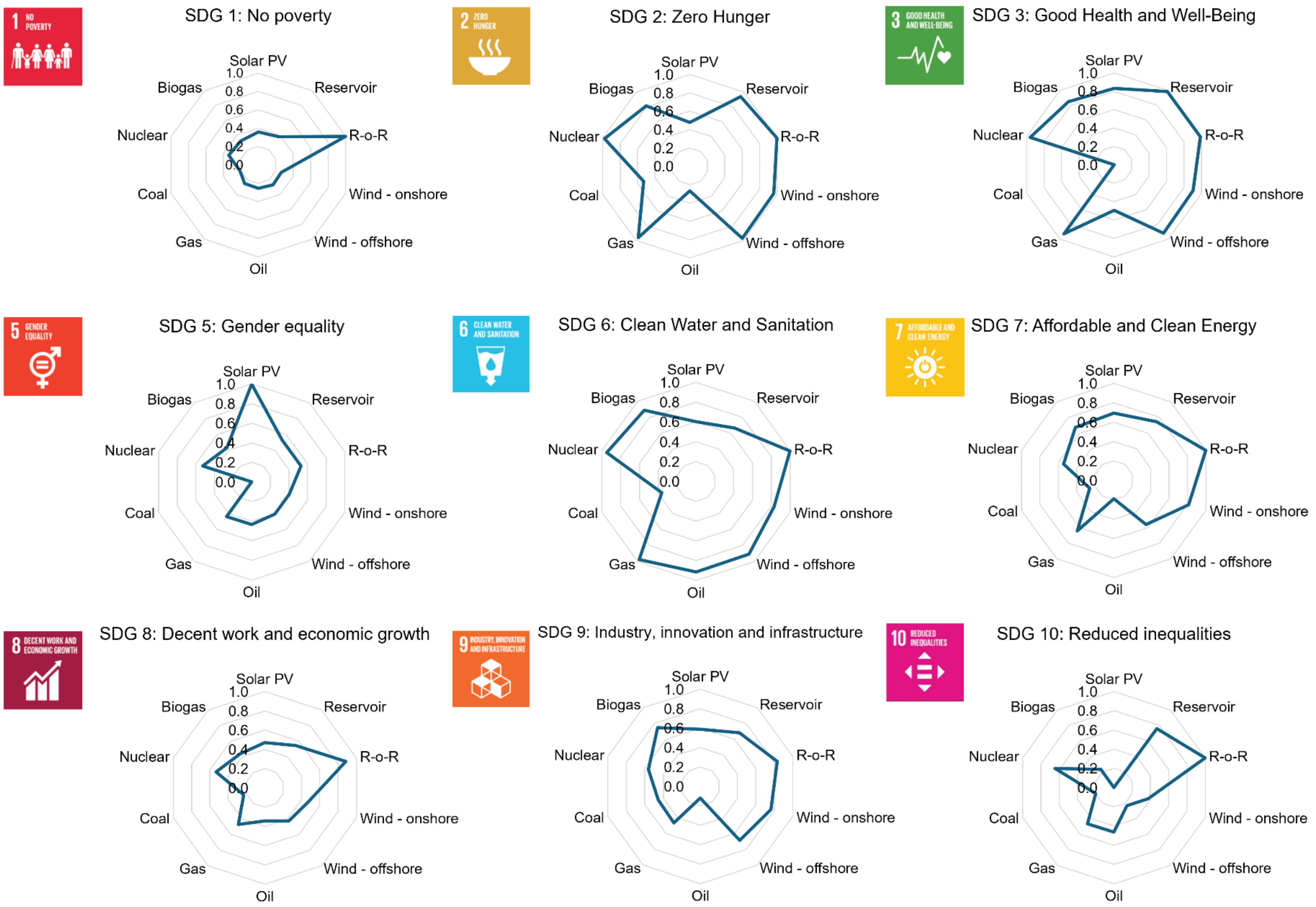
In the technological dimension (Figure 4.1b), R-o-R is also the best choice, scoring 1 (maximum value) due to its high EROI and suitability for microgrid applications. Indeed, R-o-R technology can be configured in various ways, including diversion-type plants without dams, weir-type plants, and river current systems. These configurations allow for efficient energy production with minimal environmental impact, making them suitable for microgrids, especially in remote locations where maintaining large infrastructure is challenging (Tsuanyo et al., 2023).

On the other hand, oil, offshore wind, and coal options score low in this analysis. Coal power plants require extensive infrastructure, including large-scale boilers, turbines, and a constant supply chain for coal. This makes them impractical for small-scale, decentralized setups. Also, these plants need to run continuously to be cost-effective and cannot easily be ramped up or down to match the variable demand typical of microgrids. Oil, likewise, is generally not suitable for microgrid or off-grid power generation due to its infrastructure requirements and operational constraints, while offshore wind requires significant investment and robust maintenance strategies.

Regarding the environmental dimension, Figure 4.1c exhibits hydropower options as the best alternatives, with R-o-R technology distinguished with a score of 0.97, with a bad score only in the “PSLglo Transformation” category. This result is followed by reservoir option (0.91) and offshore wind (0.88). On the other hand, coal (0.41), oil (0.44), and solar PV (0.61) present the weakest environmental scores. Regarding solar PV technology, despite being a good choice concerning climate change (GWP), it scores worse than other options regarding categories such as “Freshwater ecotoxicity”, “Marine ecotoxicity”, and “Resource use, minerals, and metals”.

These results collectively suggest that R-o-R technology is the most balanced and favorable option across social, technical, and environmental dimensions. Hydropower (both run-of-river and reservoir) and onshore wind power appear as strong candidates for sustainable power generation in the environmental dimension, while coal and oil technologies generally perform poorly across all assessed dimensions.

Finally, a weighted-normalized matrix is built considering the values of Table 4.6 for each category aggregated in the SDGs, as pointed out in Table 4.5, resulting in Figure 4.2. The final value is the mean value of the categories presented in each SDG ranging from 0 to 1. Figure 4.2 presents the aggregated results of power options for each of the selected SDGs ranging from 0 (worst performance) to 1 (best performance), based on the selected indicators. The values are detailed in Table S9.



SDG 1: No poverty
SDG 2: Zero Hunger
SDG 3: Good Health and Well-Being
SDG 5: Gender equality
SDG 6: Clean Water and Sanitation
SDG 7: Affordable and Clean Energy
SDG 8: Decent work and economic growth
SDG 9: Industry, innovation and infrastructure
SDG 10: Reduced inequalities
Solar PV
Reservoir
R-o-R
Wind - onshore
Wind - offshore
Oil
Gas
Coal
Nuclear
Biogas
1.0
0.8
0.6
0.4
0.2
0.0

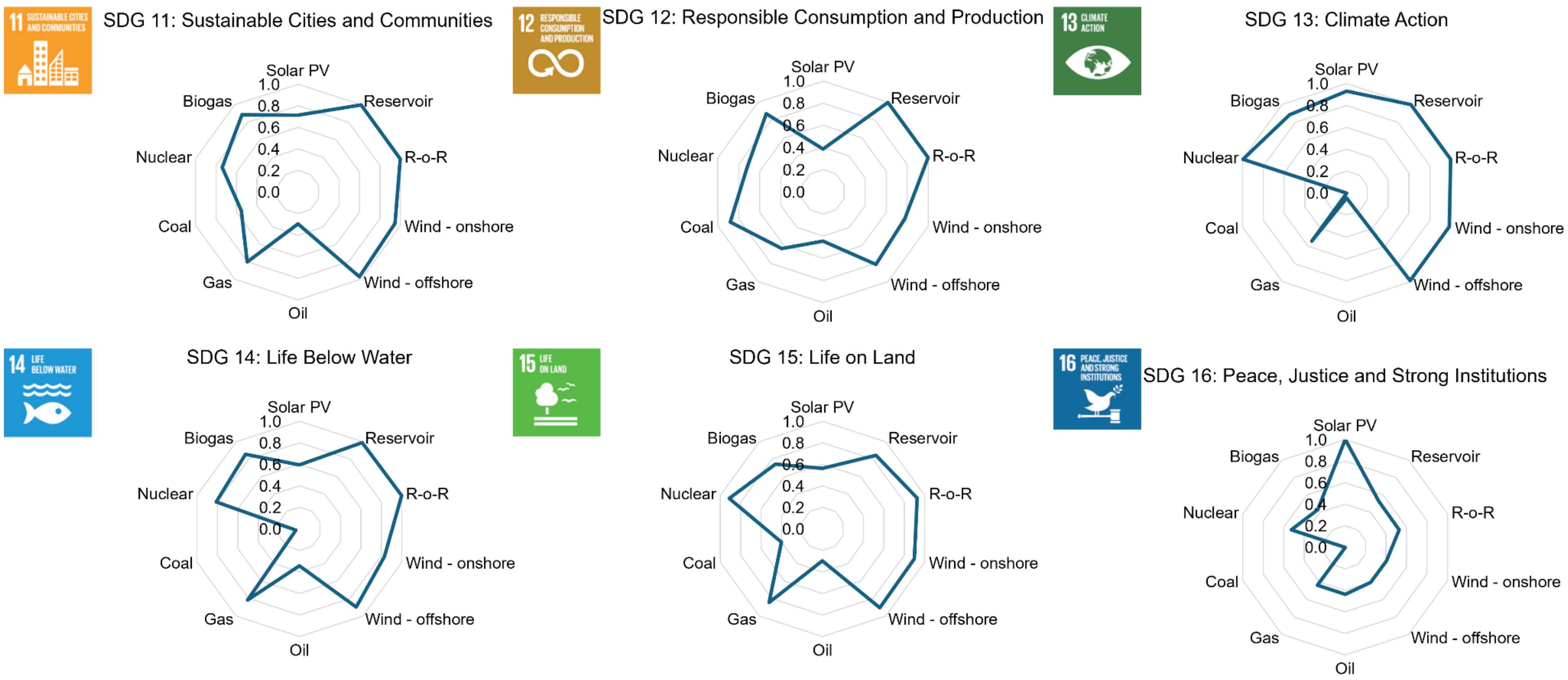


Figure 4.2 Final scores of the power options, considering social technical, and environmental dimensions, for the assessed SDGs.

A statistical analysis highlighting power options with normalized values exceeding or falling below one standard deviation (Table S10 in the supplementary material) shows the technologies that outstand their performances in different SDGs. The results indicate that solar PV technology emerges as a better option for meeting SDGs #5 (Gender equality) and #16 (Peace, justice, and strong institutions). Hydropower options show a superior performance in progressing SDGs #10 (Reduced inequalities) and #12 (Responsible consumption and production), with R-o-R showing promising outcomes also in SDGs #1 (No poverty), #7 (Affordable and clean energy), #8 (Decent work and economic growth), and #9 (Industry, innovation and infrastructure). On the other hand, coal underperforms as electricity option in SDGs #2, # 3, #5 to #8, #11, and #13 to 16. Oil, in the same way, presents low scores for meeting SDGs #2, #7 to #9, and #11 to 15. At last, solar PV presents statistically significant negative scores when it comes to seeking SDGs #2, #6, #10, and #12. This overall assessment aims to help stakeholders in choosing an electricity generation option to reinforce their prioritized SDGs.

4.3.1. Case-Study: Framework Application to Corporations

The proposed framework is tested on a set of companies from three industries: Oil & Gas (O&G), Technology, and Food & Beverage. These industries are selected for being electricity-intensive and hence challenged by the energy transition. The O&G exploration and production industry is selected for being a significant player due to its essential role in the global energy supply, projected to generate around $5.3 trillion in revenue (IBIS Word, 2024). The main companies in the sector are selected in a 12-month revenue period (Reiff, 2023).

The 'Technology' industry is included for playing a crucial role in driving global economic growth. It contributes significantly to GDP, generates employment, and fosters innovation across various sectors. The companies in this industry selected for assessment are Amazon, Alphabet, Microsoft, and Nvidia, and are among the most valuable in the world, reflecting their economic importance (CompaniesMarketcap.com, 2024). These same companies heavily utilize data centers, and it is estimated that global data center electricity consumption in 2022 was around 240-340 TWh (1.0-1.3% of global final electricity demand), excluding energy used for cryptocurrency mining, which was estimated to be around 110 TWh in 2022 (IEA, 2023a).

Finally, the Food & Beverage industry is investigated in the present study because of its major contribution to the global economy, generating significant revenue and employment, and for being energy-intensive particularly in processing and manufacturing. This segment is part of the Light Industry, comprising 30% of its emissions (IEA, 2023b), and operations such as cooking, freezing, drying, and packaging require substantial electricity to maintain efficiency and ensure food safety. The selection of companies from this industry is based on the research presented by

Sorvino (2022), considering the world's largest food companies in 2022. Each selected company has its focused SDGs, and these are presented in Table 4.7.

Table 4.7. Companies and focused SDGs

Companies	Focused SDGs	Reference
Oil & Gas industry		
Saudi Aramco	3,4,5,6,7,8,9,12,13,14,15,17	Saudi Aramco (2022)
ExxonMobil	7,12,13	ExxonMobil (2022)
Total Energies	7,8,9,13	Total Energies (2024)
Chevron	3,4,7,8,13	Chevron (2024)
Technology industry		
Microsoft	4,8,13,16	Microsoft Corporation (2023)
Alphabet (Google)	1,4,7,8,10,11,12,13,15	Alphabet (2020)
Amazon	1,2,3,4,5,6,7,8,10,12,13,14,15,16,17	Amazon (2022)
NVIDIA	3,4,9,13	NVIDIA Corporation (2023)
Food & Beverages industry		
Anheuser-Busch InBev	3,5,6,7,8,12,13,17	Anheuser-Busch InBev (2023)
Mondeléz International	2,3,6,8,12,13	Mondelēz International (2023)
Danone	2,3,6,8,12,13	Danone (2024)
Archer-Daniels-Midland Company - ADM	2,6,8,13,15	ADM (2024)

Considering the focused SDGs presented in Table 4.7, the result of the assessment is the average of the normalized values of the selected indicators/categories. The most adequate power technologies for each company and their scores are displayed in. Figure 4.3, also available in Table S11, in the supplementary material. An important highlight is that whenever a company presents SDGs using common indicators, this indicator is counted only once, preventing, therefore, double counting.

In Figure 4.3a, considering a score above one standard deviation as an indicator of acceptable performance, R-o-R emerges as the most effective power option for the Oil & Gas industry, primarily due to its superior performance in most environmental categories, both technical categories, employment indicators and the E-WFWP indicator. Reservoir power option also arises as an alternative for ExxonMobil. Conversely, oil technology statistically emerges as the worst option for all assessed companies in this industry, scoring poorly in environmental, technical, and social indicators. Coal technology is particularly unsuitable for Saudi Aramco, Total Energies, and Chevron, as it scores poorly especially in SDGs #3, #5, #13, #14, and #16.

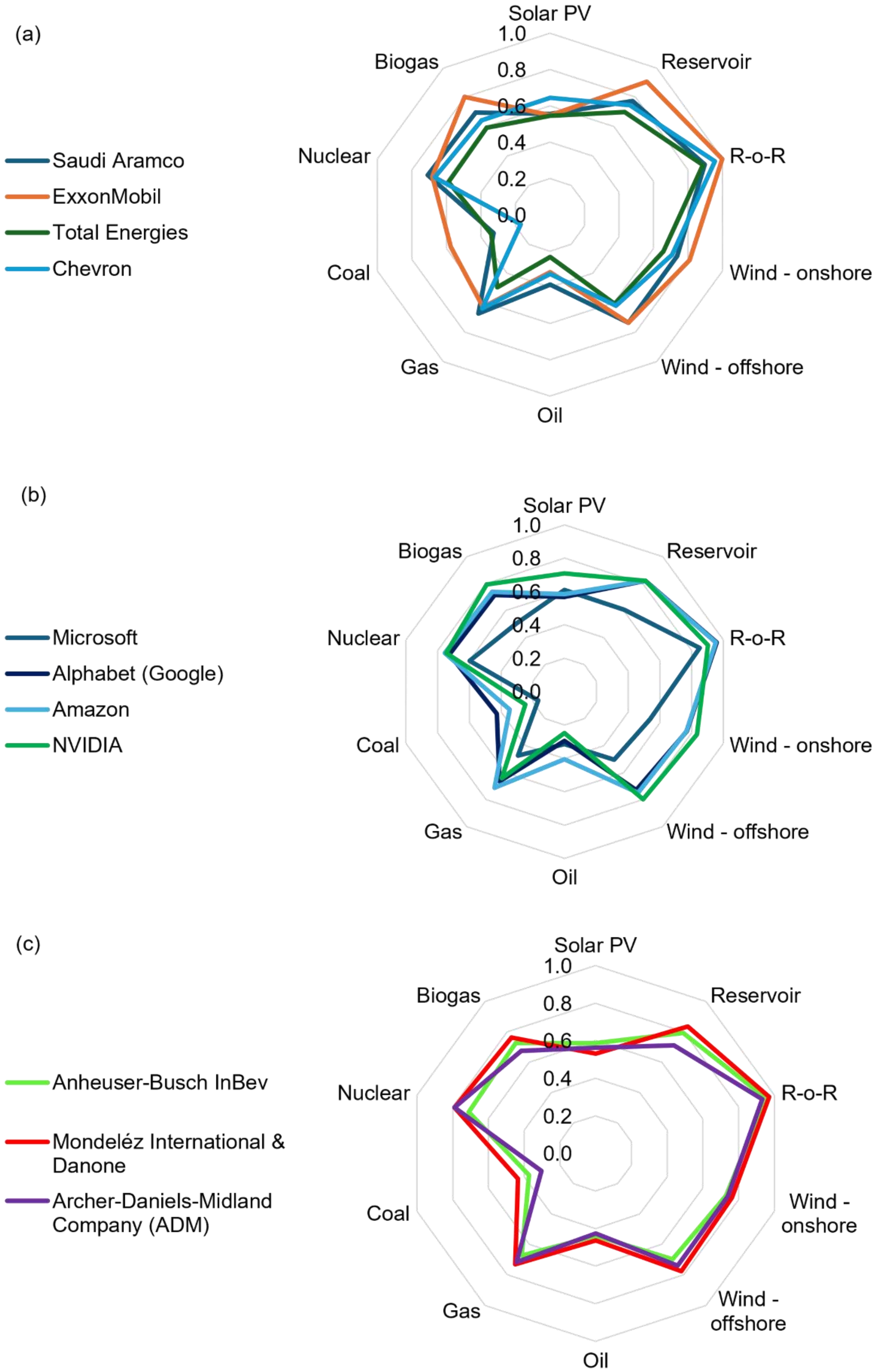


Figure 4.3 Power technology adequacy considering the company's focused SDGs. (a) Oil sector. (b) Technology sector. (c) Food & Beverages sector.

Notably, among the assessed Oil & Gas companies, only Saudi Aramco addresses the 10 SDGs identified as priority areas for the sector – #3, #6 - 9, and #12 - 17 (IPIECA, 2021). Consequently, and in the aim of pursuing the focused SDGs, the framework suggests hydropower as a viable option for the assessed companies. However, this option's availability may vary depending on regional or technical constraints. In such cases, avoiding electricity options that statistically score poorly may be a feasible alternative for maintaining SDG alignment.

Considering the energy transition trend, it is evident that Oil & Gas companies are increasingly investing in clean energy. However, direct spending on low-carbon technologies constitutes just 4% of their upstream capital expenditure (Chronis et al., 2023), with the primary challenge being to innovate while maintaining profitability. While capital strategies may gradually shift, rapid policy implementation and consumer adoption of low-carbon solutions could significantly influence long-term investment approaches. According to Kolaczkowski et al. (2021), future demand in the Oil & Gas industry will be heavily influenced by consumer preferences and expectations as consumers are increasingly making environmentally conscious purchases. This underscores the strategic imperative for the industry to better understand consumer behavior and consumption patterns, aligning the companies' pursued SDGs with consumers' prioritized concerns.

In the Technology industry (Figure 4.3b), R-o-R is an appropriate option for all the assessed companies. Like the Oil & Gas sector, oil and coal are unsuitable options for achieving the targeted SDGs, as their scores fall below one standard deviation. Unlike the energy-producing Oil & Gas industry, the Technology industry faces energy transition from a different perspective. The analyzed companies are committed to being 100% powered by renewable energy. Google achieved 100% renewable energy for its global operations in 2017 (Google, 2024), while this target is set to be reached by 2025 by Microsoft (Patron, 2023), NVIDIA (NVIDIA, 2024), and Amazon (Amazon, 2024). Additionally, Google has set their target to achieve carbon-free energy by 2030 (Google, 2024), and Amazon plans to reach net-zero carbon by 2040 (Zhai et al., 2022). Microsoft has further committed to removing its carbon footprint since its foundation in 1975, by becoming carbon negative by 2030 (Smith, 2020). The selection of the R-o-R option in most cases could support these goals, particularly considering the accessibility of the hydropower alternative in regions and availability zones of their Data Centers, such as the United States, Canada, Brazil, and Switzerland (M. Zhang, 2024c, 2024b, 2024a).

In the Food & Beverage industry (Figure 4.3c), considering the same weight of importance for the assessed indicators, R-o-R is the only statistically acceptable option for an aligned choice. Contrarily, coal and oil technologies emerge as bad options for the assessed companies due to poor scores in these dimensions. Notably, solar PV technology appears as a suboptimal choice for Mondeléz International and Danone, demonstrating particularly low performance on SDGs 2 and 12, specifically in relation to “Land use”, “Terrestrial ecotoxicity”, “Resource use, minerals and metals”, “Mineral resource scarcity”, and “Waste, non-radioactive” (Table S8).

In this industry, beyond selecting a power option, a major sustainability concern is food loss and waste. It is estimated that about 13% of food produced globally is lost between harvest and retail, while 17% of total global food production is wasted in retail, households, and food service sectors (United Nations, 2023b), leading to inefficient resources use and significant environmental impacts (Xue et al., 2024). Additionally, several SDGs, including SDG #2, #8, and #13, among others, depend on reducing the amount of food that is wasted and destroyed (Manzoor et al., 2024). These SDGs are prioritized by Mondeléz International, Danone, and Archer-Daniels-Midland Company – ADM, as presented in Table 4.7. Anheuser-Busch InBev does not focus on SDG #2 (Zero Hunger), possibly due to being a beverage company, but aligns with other SDGs, especially SDGs #6 and #12.

4.3.2. Multi-criteria decision analysis

As shown in the previous sections, different electricity options have unique advantages and disadvantages, making it challenging to identify the most sustainable choice when all aspects and indicators are given equal importance. This section addresses this complexity by analyzing the sustainability performance of electricity options with a focus on individual dimensions rather than aggregated SDGs, assigning higher weight to one dimension at a time. A sensitivity analysis is conducted by assigning a weighting factor of 5 to the dimension considered most important and a factor of 1 to the other two dimensions. This approach is based on the work of Atilgan & Azapagic (2016) and intends to assess how the relative importance of each dimension affects the overall evaluation of the options. This weighting system used in the MCDA was designed to reflect the practical reality of decision-making in sustainability contexts, where certain dimensions are often prioritized over others.

The full results are available in Table S12 in the supplementary material. The MCDA reveals that the results are robust for most companies, with Run-of-River (R-o-R) technology being statistically the most beneficial option. Conversely, coal and oil technologies are generally the least suitable in most scenarios. However, some exceptions are noted. For instance, for ExxonMobil and Total Energies, when assigning a weight five times greater to the environmental dimension, both R-o-R and Reservoir technologies emerge as suitable options aligned with the prioritized SDGs (#7, #12, and #13), which do not include social indicators but emphasize environmental ones where this technology scores well. Conversely, in this scenario for ExxonMobil, coal technology ceases to be a statistically unfavorable option.

In the Technology industry, significant changes are observed in the sensitivity analysis. For Microsoft, when the environmental dimension is weighted five times more, there is no statistically positive option, allowing for the selection of all renewable options, as well as nuclear and gas technologies.

For Nvidia (considering SDGs #3, #4, #9, and #13), overemphasizing the social dimension makes both onshore and offshore wind options acceptable, with offshore wind scoring the highest (Table S12 in the supplementary material). Although offshore wind does not score in the technological dimension due to MGO being the only impact category, it performs well in the social indicators “Manufacturing Employment Rate” and “Fatalities”. If the technological dimension is overweighted, the suitable choices become onshore wind and R-o-R. Finally, if the environmental dimension is weighted five times more, R-o-R technology reverts to being the most aligned option with the prioritized SDGs (Table S12 in the supplementary material).

In the Food & Beverage industry, solar PV is not a poor option when the social dimension is prioritized. However, it becomes unsuitable for companies like Mondeléz International and Danone when the environmental dimension is emphasized. While solar PV scores well in climate change (SDG #13), as highlighted before it performs poorly in categories such as: “Land use”; “Resource use, minerals, and metals”; “Mineral resource scarcity”; and “Waste, non-radioactive”, but also in “Freshwater ecotoxicity”, and “Fair salary potential”; influencing SDGs #2, #6, #8, and #12. “Land use” is a critical category, as efforts in this sector include increasing agricultural productivity and promoting sustainable food production systems, which are closely related to SDG #2 (Zero Hunger). “Freshwater ecotoxicity”, influencing SDG #6, is also critical, as sustainable water management is vital for food production. Therefore, industry must ensure reduced pollution and implement practices that protect water-related ecosystems. This result does not imply that solar PV is a poor technology but indicates that, for these companies, it is not the most suitable choice of electricity option aligned with their prioritized SDGs.

Therefore, the suitable options for electricity generation technologies for companies may vary depending on the intended weights assigned by stakeholders to each dimension and the SDGs prioritized by these companies. It is noticeable the existence of trade-offs and synergies among SDGs when selecting power generation technologies, emphasizing the importance of a holistic approach to decision-making to balance these trade-offs and maximize synergies. For companies, the findings suggest that aligning their power strategies with the SDGs makes them better positioned to manage regulatory and reputational risks and build resilience against future shocks. It is worth noting that the SDGs are designed with a focus on national or regional objectives, while the proposed framework aims to select, at a technology level, power options aligned with prioritized SDGs. Another limitation is that a few indicators, such as “gender equality” are more related to the company’s organizational culture, than the technology itself.

Building upon the findings, it is evident that the ongoing energy transition differs significantly from past transitions. While previous shifts were largely driven by energy efficiency and economic considerations, the current transition is predominantly influenced by social and environmental imperatives. This shift in priorities inspired the present work to adopt the SDGs as the foundational framework for evaluating electricity generation alternatives. These goals are “people-centered and planet sensitive” (UNRISD, 2014), and an integral part of the 2030 Agenda for Sustainable Development, focusing on people, planet, prosperity, peace, and partnerships (Mestdagh et al., 2024). Consequently, characterizing the contribution of a technology to a set of prioritized SDGs must mainly rely on social and environmental indicators. Future work should include country-specific efficiency data and easiness of integration to electricity grids to more accurately capture the potential of each technology in specific regions. Additionally, including economic performance indicators (e.g., capital expenditure and levelized cost of energy) would expand the practical reach of the proposed framework, providing stakeholders with a more comprehensive tool for assessing sustainability of energy generation technologies. EROI is included in the framework as a measure of energy efficiency and productivity. Consequently, it captures impacts from operational costs. A full economic assessment would require capital expenditure (CAPEX) as an economic indicator, which is a cost parcel with significant reduction from technical advancements. Furthermore, the more capital-intensive a technology, the more sensitive it is to changes in its LCOE to the discount rate (IEA, 2020c), which is strongly dependent on the region where the technology is applied. The complexity of such analysis is beyond the scope of the SDG-based comparison approached.

4.4. Conclusions of Chapter 04

A decision-support framework based on LCA was developed to assist in selecting power generation technologies aligned with prioritized SDGs of a company, a nation, or a large energy consumer seeking to align their energy procurement strategies, such as through Power Purchase Agreement (PPA), with their sustainability goals. This framework integrates environmental, social, and technical dimensions, gathers primary and secondary data, and applies in a sectoral assessment, involving twelve companies from three industrial sectors (oil & gas, technology, and food & beverage) to demonstrate its practical utility.

Run-of-River (R-o-R) is the most suitable power option overall, showing strong performance across social, technical, and environmental dimensions. When it comes to suitable power options to enforce SDGs, specifically for SDGs #5 (Gender Equality) and #16 (Peace, Justice, and Strong Institutions), solar PV is identified as the best choice to align electricity generation with SDG targets. Hydropower options show superior performance in advancing SDGs #10 (Reduced inequalities) and #12 (Responsible consumption and production), while R-o-R seems suitable when pursuing SDG #1.

Regarding sectoral implications, the framework illustrates how businesses can align their power generation choices with their prioritized SDGs. The results suggest that corporations should decide on their power generation technology based on their specific SDGs. For instance, R-o-R is the most suitable option for most cases, while Reservoir suits ExxonMobil. However, with MCDA applied, other technologies emerge as viable options, such as Reservoir for Total Energies and onshore or offshore wind for Nvidia.

It must be emphasized that the results and power option scores are a consequence of the selected indicators, categories, and the framework, and are taken globally while regional specificities would impact decisions. For example, this analysis provides average efficiency values for renewable energy sources at a global level. However, it is recognizable that renewable energy potential, and thus efficiency, can vary widely depending on regional factors such as solar irradiance or wind patterns. Future work could refine this analysis by incorporating country-specific efficiency data to more accurately reflect the potential of each technology in different regions.

A further consideration is that this study highlights how the ongoing energy transition differs from previous shifts, being driven primarily by social and environmental priorities rather than purely economic and efficiency considerations. By adopting SDGs as a framework, the analysis emphasizes the role of social and environmental indicators in evaluating electricity generation technologies. Future research could expand this approach by incorporating economic performance metrics such as CAPEX and LCOE. Although this study integrates energy efficiency through EROI, a comprehensive economic assessment considering CAPEX and regional discount rate sensitivities would further enhance the framework’s applicability and depth.

Overall, the framework provides a tool for stakeholders to make informed decisions about power generation technologies, considering their environmental, social, and technical impacts, guiding sustainable energy investments and supporting the energy transition in alignment with the SDGs. Future research verse in the refinement of the framework to incorporate more specific regional and sectoral data, enhancing its applicability and accuracy in different contexts.

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5. Discussion

The transition to sustainable energy systems is pivotal in achieving the SDGs, particularly those related to clean energy (SDG #7), climate action (SDG #13), and sustainable industrialization (SDG #9). The integration of LCA methodologies into decision-support frameworks provides a robust approach for evaluating impacts of different dimensions of various power generation technologies.

The research presented in this thesis underscores the necessity of moving away from fossil fuels towards low-carbon and renewable energy sources. This shift not only mitigates climate change but also fosters synergies among multiple SDGs, enhancing overall sustainability. However, the transition is loaded with trade-offs, as different power generation technologies can lead to unintended consequences affecting other SDGs, as discussed in Chapter 4. For instance, while renewable energy sources contribute to SDG #7 and SDG #13, their deployment can increase energy costs (impacting SDG #1 and SDG #10), require extensive land use (affecting SDG #15) as in the case of reservoir hydropower, or create social and economic disparities due to uneven access to infrastructure and employment opportunities, as in the case of reservoir, nuclear, gas and oil. Furthermore, the high initial investment required for renewable energy technologies may slow down economic growth and industrialization efforts, posing challenges to SDG #8 and SDG #9. These trade-offs highlight the need for integrated decision-making frameworks, such as the one proposed in this thesis, to balance social, environmental, and technological considerations in the energy transition process.

Therefore, trying to assess the technologies in a holistic way, Chapter 2 focused on critically reviewing the S-LCA in the power sector, providing a general insight into the state-of-the-art of the reviewed literature related to S-LCA in the electricity generation sector. This section highlights the inconsistencies in defining system boundaries, functional units, and stakeholder categories. It also emphasizes the need for standardized methodologies and a broader range of social indicators to enhance the role of S-LCA as a decision-making tool in the power sector. This chapter evidences the need for indicators that can compare different technologies, but also gives recommendations related to system boundaries to be adopted.

The system boundaries suggested in Chapter 2, along with the most frequently cited groups of social indicators identified in the same chapter and the Type II impact assessment approach, were adopted in Chapter 4 to ensure consistency and methodological rigor. These boundaries were maintained to enhance comparability and transparency, as recommended by Pollok et al. (2021). Additionally, indicators that could be classified under multiple dimensions were carefully analyzed and managed to prevent double counting, in alignment with the concerns raised by Volkart et al. (2017).

Considering the lack of consensus on social indicators discussed in Section 1.4 and the most frequently cited groups of social indicators identified in Chapter 2, Chapter 3 introduces an innovative methodology: the E-WFWP assessment. This approach aims to identify and implement socially sustainable electricity generation options by combining fair wage considerations with employment potential. By offering a fresh perspective on social sustainability assessment in the power sector, this methodology seeks to influence policy and decision-making, fostering more socially responsible energy solutions.

The proposed indicator in Chapter 3 intends to enhance the reliability and credibility of S-LCA outcomes, enabling more effective comparisons of the social performance across different power technologies. By fostering trust among stakeholders, consumers, and investors, it provides a robust and well-structured tool that benefits the power sector, promoting more informed and socially responsible decision-making.

Finally, Chapter 4 introduces additional social and technological indicators, such as gender equality, E-WFWP, and EROI, which are quantified using primary corporate and sectoral data, complementing pre-established environmental categories, to propose a novel framework. This framework addresses the lack of integrated models capable of evaluating the multidimensional impacts of various power generation technologies in alignment with the SDGs. With its global perspective and expanded range of social and technical indicators, the framework is designed to be applicable to corporations across diverse sectors, providing a comprehensive tool for sustainable energy decision-making.

The framework presented in Chapter 4 explicitly aligns global sustainability targets (SDGs) with tailored environmental, social, and technical indicators for power generation technologies. Unlike previous studies that treated SDGs as abstract goals, this framework operationalizes SDGs by linking them with quantifiable indicators and facilitating decision-making based on prioritized SDGs of corporations or sectors, ensuring a practical and measurable pathway for stakeholders to align energy choices with sustainability goals. It expands the geographical focus beyond regional studies like those of Henzler et al. (2020) and Souza et al. (2022), encompassing the global power sector.

The proposed method advances the integration of social and technical indicators in sustainability assessments by incorporating dimensions often overlooked in conventional frameworks. This enhances the applicability of the framework across multiple industries, as presented in Chapter 4 (Oil & Gas, Technology, and Food & Beverage), and by employing an MCDA approach to evaluate the power options, the method generates quantitative and actionable insights, addressing the limitations of qualitative heuristic approaches like those presented by Hannouf et al. (2023). The importance of MCDA employment is that it enables the ranking of technologies based on their performance across multiple dimensions, facilitating a systematic and transparent decision-making process.

By integrating a life cycle approach, covering environmental, social, and technical aspects of power generation technologies, the framework is aligned with the triple bottom line of sustainable development, ensuring a comprehensive evaluation. Also, by using life cycle data, it captures impacts across all stages of electricity generation, from resource extraction to decommissioning (considering the boundaries established by Chapter 2), providing a holistic view of sustainability.

It is worth noting that the proposed method supports power procurement strategies, such as PPAs, enabling companies to align energy decisions with their ESG objectives, and enables stakeholders to make informed choices about power generation technologies by highlighting the trade-offs and synergies involved. For instance, as seen in Chapter 4, while R-o-R hydropower is a balanced choice across social, technical, and environmental dimensions, specific technologies like solar PV and biogas are adequate for targeted SDGs. On the other hand, technologies like coal and oil are consistently poor choices due to their adverse environmental and social impacts.

Case studies from the industrial sectors – Oil & Gas, Technology, and Food & Beverage – demonstrate the practical application of this framework. They reveal that aligning energy choices with prioritized SDGs can guide sustainable investments and operational strategies. Notably, the framework suggests that while some technologies, like solar PV, excel in some SDGs (e.g., SDG #5 and SDG#16), they may fall short in others (e.g., SDG #10 and SDG#12), necessitating a balanced approach.

The energy sector's future lies in integrating renewable energy technologies, optimizing energy efficiency, and ensuring equitable access to energy. Policymakers, industry leaders, and stakeholders must adopt comprehensive LCA-based decision-making tools to navigate the complexities of the energy transition effectively. By doing so, they can ensure that the pursuit of clean and affordable energy does not come at the expense of other critical sustainability goals.

Overall, the proposed framework has proven effective in assessing the sustainability of power generation technologies, providing an integrated approach. The application of the model in case studies indicated that the inclusion of social indicators, such as the E-WFWP, enables a more holistic analysis of energy options, allowing decisions to be aligned with the SDGs. The incorporation of this indicator represents methodological advancement, as it addresses a gap frequently overlooked in the LCA literature while reinforcing the relevance of social aspects in the sustainable energy transition. Furthermore, the model has demonstrated flexibility for different business contexts, highlighting its practical applicability in supporting decision-making.

Despite these advancements, some limitations remain and may impact the widespread adoption of the framework. One of the main challenges is the reliance on secondary data, which can compromise the accuracy of assessments, particularly concerning the specific social impacts of each locality. The unavailability of detailed and up-to-date databases limits the precision of estimates, making the use of primary data collected directly from companies and affected communities highly desirable. Additionally, the absence of consensus on the definition and quantification of social criteria, such as fair wages and gender equality, represents a barrier to the uniform application of the methodology.

Another key issue is the operationalization of the framework, which may present challenges for companies and researchers who lack expertise in S-LCA. The need for multiple criteria and data sources increases the complexity of the analysis, making it essential to develop automated tools that facilitate the model's application. Although the study has demonstrated the model's feasibility, its large-scale implementation will require additional efforts to make it more accessible and replicable.

An additional limitation is that the adopted approach prioritized the assessment of social impacts throughout the life cycle of electricity generation but did not thoroughly consider indirect effects, such as changes in the supply chain and secondary social impacts on communities. This limitation is partly due to the lack of robust methodologies for quantifying these effects, representing an open field for future improvements.

Overcoming these limitations requires enhancements in data collection and the refinement of the methodologies used. One of the main opportunities is the integration of real-time primary data, which could be facilitated through partnerships with power sector companies and the use of emerging technologies.

Additionally, artificial intelligence (AI) and blockchain could enhance data traceability and assessment robustness, enabling more dynamic and reliable analyses. AI could be used to fill data gaps and identify patterns in large datasets, while blockchain technology could ensure data transparency and authenticity.

Finally, expanding the geographical and sectoral scope of the framework could make it more applicable to different economic and social realities. Future studies should consider adapting the model to specific regional contexts and sectors beyond electricity generation, exploring how the methodology can be applied to sustainable decision-making across various industries. These improvements will not only strengthen the reliability of S-LCA in the energy sector but also contribute to its broader adoption as a strategic tool for public policy formulation and corporate governance focused on sustainability.

6. Conclusions

This thesis has addressed key challenges and opportunities in the sustainability assessment of power generation technologies through the lens of S-LCA, with a particular emphasis on advancing methodological frameworks and aligning them with the SDGs. A critical review of S-LCA applications in the power sector revealed significant gaps in standardization, such as inconsistencies in system boundaries, functional units, and stakeholder categories. Among the 92 analyzed studies, employment and occupational safety indicators were dominant, highlighting the potential of S-LCA to provide a comprehensive understanding of the social dimensions in energy systems. These findings emphasize the importance of advancing methodologies to support the achievement of SDGs #1 (No Poverty), #7 (Affordable and Clean Energy), and #8 (Decent Work and Economic Growth).

Building on these insights, this research proposed novel social indicators, including the Employment-Weighted Fair Wage Potential, which integrates fair wage and employment metrics to evaluate the social sustainability of power generation technologies. This indicator, alongside others such as manufacturing employment rate, occupational accidents, fatalities, and gender equality, provides a more nuanced perspective on social performance. By identifying social hotspots and addressing fair labor conditions, these tools enable decision-making that aligns with the SDGs and fosters socially responsible energy transitions.

The development of a life cycle-based decision-support framework further strengthens the contributions of this thesis. Designed to guide corporations in selecting power generation technologies that align with prioritized SDGs, the framework integrates environmental, social, and technical dimensions into a holistic approach to sustainability. A case study demonstrated its applicability across diverse sectors, revealing how tailored strategies can accelerate SDG alignment. The results underline that different technologies are more suitable for achieving specific SDGs, reinforcing the necessity of context-specific solutions.

Despite these advancements, some limitations remain. The reliance on secondary data and the lack of standardization in social indicators pose challenges to broader application, underscoring the need for improved data collection, particularly site-specific and real-time information. Expanding the framework's geographical and sectoral scope could also enhance its applicability, providing more comprehensive insights into cross-sectoral sustainability. Additionally, integrating emerging technologies, such as AI and blockchain, could improve data traceability and analytical precision, further advancing S-LCA methodologies.

Overall, this work contributes to the growing body of knowledge on S-LCA by addressing its current limitations and expanding its applicability within the power sector. The alignment of methodological advancements with the SDGs not only facilitates more socially responsible energy transitions but also lays the groundwork for future interdisciplinary research that unites social, environmental, and technical dimensions into a cohesive sustainability framework. Standardization in S-LCA methodologies, particularly in defining system boundaries, functional units, and selecting social indicators, remains a critical priority to enhance the comparability and reliability of results.

The findings of this thesis underscore the importance of holistic sustainability assessments that balance environmental, social, and technical dimensions, preventing the transfer of burdens from one aspect to another. The proposed framework offers actionable insights for policymakers, emphasizing the need for policies that support the integration of social dimensions into sustainability assessments and promote socially sustainable power generation technologies. Companies aligning their strategies with the SDGs can better manage risks, build resilience against future shocks, and identify power generation options that positively contribute to their sustainability goals. Collectively, these conclusions highlight the value of a multi-dimensional approach to sustainability in the power sector, ensuring that environmental gains are achieved without compromising social well-being.

Appendix A - Supplementary Material for Chapter 02

Supplementary material: Illustration of the georeferenced case studies; Selected works of S-LCA of electricity generation technologies based on the systematic review criteria; and List of the multi-criteria decision analysis (MCDA) methods used in the reviewed literature.

Figure S1 Georeferenced case studies (when informed).

Table S.1 S-LCA of electricity generation technologies: Overview of the selected works based on the systematic review criteria.

Authors	Title	One-phrase abstract	Functional Unit	System Boundary	Nº of stakeholders (declared and/or inferred from the text)	Nº of social / socio-economic indicators	Type of assessment method
Akber et al. (2017)	Life cycle sustainability assessment of electricity generation in Pakistan: Policy regime for a sustainable energy mix	LCSA of the Pakistani electricity sector	Generation of 1kWh	Cradle-to-gate	2	4	Both
Atilgan & Azapagic (2016)	An integrated life cycle sustainability assessment of electricity generation in Turkey	LCSA of the Turkish electricity sector	Generation of 1kWh of electricity in Turkey	Cradle-to-grave	2	6	Both
Atilgan & Azapagic (2017)	Energy challenges for Turkey: Identifying sustainable options for future electricity generation up to 2050	LCSA of 14 different electricity scenarios for Turkey up to 2050	Generation of 1kWh Total annual electricity generation	Cradle-to-grave	2	5	Type II
Aung et al. (2021)	Social impacts of large-scale hydropower project in Myanmar: a social life cycle assessment of Shweli hydropower dam 1	Case study of adverse social life cycle impacts of hydropower generation in Myanmar	1 MWh of net electricity production from a hydropower plant in a 100-year life span	Gate-to-gate	4	>15	Type I
Azapagic et al. (2016)	Towards sustainable production and consumption: A novel DEcision-Support Framework IntegRating Economic, Environmental and Social Sustainability (DESIRES)	LCSA framework proposition and application on UK's electricity generation technologies and scenarios	Generation of 1kWh, 1 TWh, 1 PWh Dimensionless (for one or more indicators) m^3	Cradle-to-grave	9	14	Both
Bachmann (2013)	Towards life cycle sustainability assessment: Drawing on the NEEDS project's total cost and multi-criteria decision analysis ranking methods	Analysis of two integrated sustainability assessments in view of potential further developments of LCSA	Generation of 1kWh	Unspecified	1	>15	Both

Backes et al. (2021)	Life Cycle Sustainability Assessment of a dish-Stirling Concentrating Solar Power Plant in the Mediterranean area	LCSA of a dish-Stirling Concentrating Solar Power Plant located in Palermo	One power plant	Cradle-to-use	3	>15	Both
Benedict (2017)	Understanding Full Life-cycle Sustainability Impacts of Energy Alternatives	Sustainability review	Unspecified	Unspecified	3	3	Both
Bentsen et al. (2019)	Dynamic sustainability assessment of heat and electricity production based on agricultural crop residues in Denmark	Review of sustainability of cereal straw used for heat and electricity production in Denmark	Unit of energy produced (MJ, TJ, PJ)	Unspecified	2	3	Type II
Bonilla-Alicea & Fu (2022)	Social life-cycle assessment (S-LCA) of residential rooftop solar panels using challenge-derived framework	Evaluation of the social impacts of rooftop solar panels	Unspecified	Gate-to-grave	4	>15	Type I
Buchmayr et al. (2022)	Exploring the global and local social sustainability of wind energy technologies: An application of a social impact assessment framework	Framework proposition for quantifying well-being impacts of energy technologies	Generation of 1MWh or 1 TWh deliverd to the grid	Cradle-to-gate	3	>15	Both
Caballero et al.(2023)	Energy justice & coastal communities: The case for Meaningful Marine Renewable Energy Development	Synthesize lessons learned to inform future directions for Meaningful MRE development	Unspecified	Cradle-to-grave	8	>15	Type I
Cartelle Barros et al. (2015)	Assessing the global sustainability of different electricity generation systems	An assessment model to compare energy systems based on integral sustainability criteria, using MIVES method	Unspecified	Cradle-to-gate	1	5	Both
Cartelle et al. (2015)	Indicators for assessing sustainability of power plants: environmental, social, economic and technical aspects	Presentation of indicators to use in a power plant sustainability assessment model	MW of installed power	Cradle-to-grave	3	10	Both
Claudia Roldán et al. (2014)	Scenarios for a hierarchical assessment of the global sustainability of electric power plants in México	Sustainability assessment of nine electric power plants in Mexico	Unspecified	Cradle-to-grave	2	2	Type II
Contreras-Lisperguer et al. (2018)	Sustainability assessment of electricity cogeneration from sugarcane bagasse in Jamaica	LCSA of bioelectricity generation by sugarcane	To generate bioelectricity for a year in a sugar mill in Jamaica	Cradle-to-gate	2	12	Both
Cooper et al. (2018)	Social sustainability assessment of shale gas in the UK	Evaluation of social impacts of shale gas production for generation and comparison to other electricity options electricity	Generation of 1 TWh Dimensionless (for one or more indicators)	Cradle-to-grave	8	14	Both

Corona & San Miguel (2019)	Life cycle sustainability analysis applied to an innovative configuration of concentrated solar power	LCSA case study of CSP in the Spanish electricity sector	1 MWh of electricity poured into the grid	Cradle-to-gate	9	>15	Both
Corona et al. (2017)	Social Life Cycle Assessment of a Concentrated Solar Power Plant in Spain: A Methodological Proposal	New assessment method, presenting a S-LCA case study applied to CSP plant	Generation of 1MWh	Cradle-to-gate	4	>15	Type I
Dombi et al. (2014)	Sustainability assessment of renewable power and heat generation technologies	Case study of renewable energy sources (RES) technologies	Unit of energy produced (e.g. MJ, TJ, PJ)	Unspecified	5	2	Both
Dorini et al. (2011)	Managing uncertainty in multiple-criteria decision making related to sustainability assessment	Handling uncertainty with MCDA and case study	Generation of 1kWhYearkmt	Unspecified	4	9	Type II
Evans & Strezov (2010)	A sustainability assessment of electricity generation	Sustainability assessment of electricity generation according to eight key sustainability indicators	Average value per kilowatt hour	Cradle-to-grave	-	11	NS
Evans et al. (2009)	Assessment of sustainability indicators for renewable energy technologies	Sustainability rank of no combustion renewable energy technologies	Generation of 1kWh	Cradle-to-grave	2	10	Type I
Fattahi et al. (2021)	Sustainable supply chain planning for biomass-based power generation with environmental risk and supply uncertainty considerations: a real-life case study	Development of a two-stage stochastic programme (TSSP) for sustainable planning of Supply Chain networks	Unspecified	Unspecified	4	4	Both
Fois et al. (2022)	Social impact assessment of wind power generation. An innovative method for decision making processes	New method based on the evaluation of environmental, social, and economic indicators	Generation of 1kWh	Cradle-to-gate	11	>15	Type I
Fortier et al. (2019)	Introduction to evaluating energy justice across the life cycle: A social life cycle assessment approach	Discussion of how social LCA can address energy justice for stakeholders	Unspecified	Cradle-to-grave	4	>15	Both
Galán-Martín et al. (2016)	Enhanced data envelopment analysis for sustainability assessment: A novel methodology and application to electricity technologies	Novel approach based on MCDA to quantify the level of sustainability	Generation of 1kWh	Cradle-to-grave	4	6	Type II
Gallego Carrera & Mack (2010)	Sustainability assessment of energy technologies via social indicators: Results of a survey among European energy experts	Assessment of energy technologies using expert judgments with indicators generated in a discursive process	Unspecified	Unspecified	10	9	Type I

Genoud & Lesourd (2009)	Characterization of sustainable development indicators for various power generation technologies	Sustainability assessment of electricity technologies	Unspecified	Unspecified	3	6	NS
Gumus et al. (2016)	Intuitionistic fuzzy multi-criteria decision making framework based on life cycle environmental, economic and social impacts: The case of U.S. wind energy	Presentation of an intuitionistic fuzzy TOPSIS method and case study	Unspecified	Cradle-to-gate	3	5	Both
Guo et al. (2020)	Life cycle sustainability assessment of pumped hydro energy storage	LCSA of energy storages (CPHES and UPHES)	kW of installed power	Cradle-to-grave	2	5	Type II
Hallste Pérez et al. (2023)	Inclusion of key social indices for a comparative assessment of the sustainability of the life cycle of current and future electricity generation in Spain: A proposed methodology	Development of a methodology that expands the number of key social indicators calculated within an LCSA	Generation of 1GWh	Cradle-to-grave	3	10	Type I
Hemdi et al. (2013)	Sustainability evaluation using fuzzy inference methods	Proposition of a methodology for integrating a fuzzy approach into a sustainability evaluation	Unspecified	Unspecified	-	5	Both
Hong et al. (2013)	Evaluating options for sustainable energy mixes in South Korea using scenario analysis	Assessment of sustainable energy options in South Korea based on an hourly modelling approach	Unspecified	Unspecified	-	1	Type II
Huang et al. (2018)	Economic and Social Impact Assessment of China's Multi-Crystalline Silicon Photovoltaic Modules Production	Exploration of socioeconomic impact assessment for PV modules in China	mc-Si PV module with capacity of 200 watt peak capacity (Wp)	Cradle-to-gate	2	4	Type II
J. Li et al. (2023)	Life cycle sustainability assessment and circularity of geothermal power plants	Review of the sustainability and circularity of geothermal power plants	Unspecified	Cradle-to-grave	2	5	NS
Kabayo et al. (2019)	Life-cycle sustainability assessment of key electricity generation systems in Portugal	LCSA of the Portuguese electricity sector	Generation of 1kWh	Cradle-to-grave	2	5	Type II
Kaiser et al. (2022)	Social and Environmental Assessment of a Solidarity Oriented Energy Community: A Case-Study in San Giovanni a Teduccio, Napoli (IT)	Evaluation of sustainability of the Solidarity Oriented Renewable Energy Communities	Unspecified	Cradle-to-gate	8	>15	Both
Khatami & Goharian (2022)	Beyond Profitable Shifts to Green Energies, Towards Energy Sustainability	Compilation of metrics based on the *Relative Aggregate Footprint* method to energy technologies	Unspecified	Unspecified	2	4	Both

Klein & Whalley (2015)	Comparing the sustainability of U.S. electricity options through multi-criteria decision analysis	Sustainability comparison of 13 options for new US electricity generation using MCDA	Generation of 1GWh	Cradle-to-grave	6	2	Type II
Ko et al. (2018)	Sustainability Assessment of Concentrated Solar Power (CSP) Tower Plants – Integrating LCA, LCC and LCWE in one Framework	Sustainability assessment of a CSP tower plant	1 kWh net electricity fed to the grid	Cradle-to-grave	1	2	Both
Kouloumpis & Azapagic (2018)	Integrated life cycle sustainability assessment using fuzzy inference: A novel FELICITA model	Proposition of a MCDA model to help deal with imprecise and uncertain information	Generation of 1 TWh Generation of 1 PWh	Cradle-to-grave	2	3	Type II
Kumar et al. (2023)	Life cycle based feasibility indicators for floating solar photovoltaic plants along with implementable energy enhancement strategies and framework-driven assessment approaches leading to advancements in the simulation tool.	Review of floating solar PV plants and proposition of a conceptual simulation tool for its efficiency modelling	Unspecified	Unspecified	4	>15	NS
Lassio et al. (2021)	Life cycle-based sustainability indicators for electricity generation: A systematic review and a proposal for assessments in Brazil	Review and proposition of indicators for the electricity generation in Brazil	Unspecified	Unspecified	4	4	Both
Lehmann et al. (2022)	Towards social Life Cycle Assessment of Energy Systems: a case study on offshore wind farms from companies' perspective	Integration of the companies' perception on stakeholders and social impacts to be considered in the offshore wind sector	Unspecified	Cradle-to-grave	5	>15	Type I
Lin et al. (2022)	An innovative sustainability-oriented multi-criteria decision making framework for prioritization of industrial systems with interdependent factors: Method and a case study of electricity generation	Development of a life cycle sustainability decision making method	The value of parameters generated by each alternative power plant when producing 1 kW of electricity	Cradle-to-grave	1	2	Type II
Luu & Halog (2016)	Rice Husk Based Bioelectricity vs. Coal-fired Electricity: Life Cycle Sustainability Assessment Case Study in Vietnam	LCSA of rice husk-based bioelectricity in Vietnam	Generation of 1MWh	Cradle-to-gate	4	7	Both
Manzini Poli et al. (2022)	Sustainability Assessment of Solid Biofuels from Agro-Industrial Residues Case of Sugarcane Bagasse in a Mexican Sugar Mill	Case study of sustainability assessment of energy systems using solid biofuels for heat and power generation	Generation of 1kWh	Cradle-to-gate	2	1	Type II

Martínez-Guido et al. (2021)	The integration of pelletized agricultural residues into electricity grid: Perspectives from the human, environmental and economic aspects	Evaluation of potential benefits from the production of fuel pellets using agricultural residues	Unspecified	Cradle-to-gate	1	1	Type II
Martinez-Hernandez et al. (2022)	Modelling to analyse the process and sustainability performance of forestry-based bioenergy systems	Novel process model and sustainability analysis of bioenergy in Mexico	Generation of 1MWe	Cradle-to-grave	3	12	Both
Martín-Gamboa et al. (2020)	A protocol for the definition of supply chains in product social life cycle assessment: application to bioelectricity	Novel approach that enlarges the scope to identify supply-chain paths	Generation of 1kWh	Cradle-to-gate	2	5	Type I
Martín-Gamboa et al. (2021)	Comparative Social Life Cycle Assessment of Two Biomass-to-Electricity Systems	Case study of biomass electricity S-LCA in Portugal	1 kWh of electricity delivered to the grid	Cradle-to-gate	2	6	Type I
Martín-Gamboa et al. (2022)	Definition, assessment and prioritisation of strategies to mitigate social life-cycle impacts across the supply chain of bioelectricity: A case study in Portugal	Proposition of a framework to mitigate social life cycle impacts across the supply chain of energy products	Generation of 1kWh of bioelectricity	Cradle-to-gate	2	6	Type I
Masilela & Pradhan (2021)	A life cycle sustainability assessment of biomethane versus biohydrogen – For application in electricity or vehicle fuel? Case studies for African context	LCSA comparison: producing and applying biomethane versus bio-H_2 for power generation or transportation fuel	Energy recovery from 1 kg of volatile solids (VS)	Cradle-to-gate	2	9	Type I
Maxim (2014)	Sustainability assessment of electricity generation technologies using weighted multi-criteria decision analysis	Sustainability rank of electricity generation technologies	Dimensionless Unit of electricity produced	Cradle-to-grave	3	4	Both
Moslehi & Arababadi (2016)	Sustainability Assessment of Complex Energy Systems Using Life Cycle Approach-Case Study: Arizona State University Tempe Campus	Sustainability evaluation and comparison of two different electricity generation fuel mixes	Electricity generation mix for ASU's Tempe campus	Cradle-to-grave	2	3	Both
Nagarkatti & Kolar (2021)	Life Cycle Based Sustainability Index of Coal Power Plants in India	Sustainability estimation on a life cycle basis with the help of MCDA	Dimensionless MW of installed power	Cradle-to-grave	2	2	Type II
Nock & Baker (2019)	Holistic multi-criteria decision analysis evaluation of sustainable electric generation portfolios: New England case study	Methodology presentation for evaluating the sustainability of a region's electricity sector, using MCDA	Dimensionless GWh	Unspecified	6	3	Both
Noori et al. (2015)	A macro-level decision analysis of wind power as a solution for sustainable energy in the USA	Quantification of socio-economic and environmental impacts of producing wind-power for the US electricity mix	Generation of 1kWh	Cradle-to-use	3	5	Type II

Nubi et al. (2021)	A Prospective Social Life Cycle Assessment (sLCA) of Electricity Generation from Municipal Solid Waste in Nigeria	Assessment of the social impacts potentially arising from the adoption of WtE in Lagos and Abuja, Nigeria	The prospective management of MSW for WtE electrical power generation in Lagos and Abuja, Nigeria	Unspecified	4	>15	Type I
Nubi et al. (2022)	Life Cycle Sustainability Assessment of Electricity Generation from Municipal Solid Waste in Nigeria: A Prospective Study	LCSA of four different prospective Waste-to-Energy systems in Nigeria	Unspecified	Unspecified	4	>15	Type I
Pérez-Denicia et al. (2021)	Suitability assessment for electricity generation through renewable sources: towards sustainable energy production	Establishment of suitable locations for power generation in Mexico, as well as the most reliable renewable technologies	Unspecified	Unspecified	2	12	Type II
Prasara-A et al. (2019)	Environmental and social life cycle assessment to enhance sustainability of sugarcane-based products in Thailand	Identification of hotspots and sustainability improvement opportunities of selected products from sugarcane	1000 t of processed sugarcane	Cradle-to-gate	2	14	Type I
Rashid & Majed (2023)	Integrated life cycle sustainability assessment of the electricity generation sector in Bangladesh: Towards sustainable electricity generation	Evaluation of integrated sustainability of Bangladesh's electricity generation	Generation of 1kWh	Cradle-to-gate	2	4	Both
Ren (2018)	Multi-criteria decision making for the prioritization of energy systems under uncertainties after life cycle sustainability assessment	Development of a life cycle sustainability prioritization framework	Generation of 1kWh Generation of 1MWh	Cradle-to-grave	2	3	Type II
Rodríguez-Serrano et al. (2017)	Assessing the three sustainability pillars through the Framework for Integrated Sustainability Assessment (FISA): Case study of a Solar Thermal Electricity project in Mexico	Sustainability impact assessment of the supply chain of a Solar Thermal Electricity project in Mexico	Whole project	Unspecified	3	>15	Both
Roinioti & Koroneos (2019)	Integrated life cycle sustainability assessment of the Greek interconnected electricity system	LCSA of the Greek interconnected electricity system	Generation of 1kWh	Cradle-to-gate	5	6	Both
Sadhukhan et al. (2021)	The Mathematics of life cycle sustainability assessment	Discussion of a transferable approach to LCSA of engineering systems	Generation of 1GWh	Cradle-to-cradle	-	0	Type I
Sadiq et al. (2023)	Sustainability assessment of renewable power generation systems for scale enactment in off-grid communities	Sustainability assessment of scaled RES for off-grid households.	Unspecified	Unspecified	6	5	Both

San Miguel & Cerrato (2020)	Life Cycle Sustainability Assessment of the Spanish Electricity: Past, Present and Future Projections	Sustainability evaluation of Spanish electricity system	Generation of 1MWh	Cradle-to-gate	1	1	Type II
Santoyo-Castelazo & Azapagic (2014)	Sustainability assessment of energy systems: Integrating environmental, economic and social aspects	New decision-support framework for an integrated sustainability assessment of energy systems, in Mexico	Annual generation of electricity in 2050	Cradle-to-grave	3	11	Both
Shaaban et al. (2018)	Sustainability Assessment of Electricity Generation Technologies in Egypt Using Multi-Criteria Decision Analysis	Implementation of two MCDA methodologies to perform a sustainability assessment of power technologies	Dimensionless MW of installed power	Cradle-to-gate	1	3	Both
Souza et al. (2022)	Addressing the contributions of electricity from biomass in Brazil in the context of the Sustainable Development Goals using life cycle assessment methods	Interactions and trade-offs of different electricity-production options related to their contribution to selected SDGs	Generation of 1kWh	Cradle-to-gate	1	8	Type II
Stamford & Azapagic (2011)	Sustainability indicators for the assessment of nuclear power	Identification of appropriate sustainability criteria in the context of UK electricity generation	Generation of 1kWh Generation of 1GWh Dimensionless m³	Cradle-to-grave	8	>15	Both
Stamford & Azapagic (2012)	Life cycle sustainability assessment of electricity options for the UK	LCSA of the UK's electricity sector	Generation of 1kWh Generation of 1GWh Dimensionless m³	Cradle-to-grave	4	15	Type II
Stamford & Azapagic (2014)	Life cycle sustainability assessment of UK electricity scenarios to 2070	LCSA of the UK' electricity sector up to 2070	Generation of 1kWh Generation of 1GWh Generation of 1 TWh Generation of 1 PWh Dimensionless m³	Cradle-to-grave	4	14	Both
Stougie et al. (2012)	Electricity production from renewable and nonrenewable energy sources: A comparison of environmental, economic and social	Investigation of whether exergy analysis can be helpful in choosing between different energy supply options	Unit of energy produced (e.g. MJ, TJ, PJ)	Unspecified	1	1	Type II

	sustainability indicators with exergy losses throughout the supply chain						
Stougie et al. (2015)	Sustainability assessment of power generation systems by applying exergy analysis and LCA methods	Case study applying Total Cumulative Exergy Loss method and the exergy replacement costs of minerals	Unit of energy produced (e.g. MJ, TJ, PJ)	Cradle-to-grave	1	1	Type II
T. Li et al. (2017)	A Regional Life Cycle Sustainability Assessment Approach and its Application on Solar Photovoltaic	Proposition of a sustainability assessment method and case study	Generation of 1kWh	Unspecified	1	3	Type II
T. Li et al. (2018)	Life cycle sustainability assessment of grid-connected photovoltaic power generation: A case study of Northeast England	Regional LCSA model proposition and case study of solar PV technology	Unit of electricity produced	Cradle-to-grave	5	2	Type II
Takeda et al. (2019)	Are renewables as friendly to humans as to the environment?: A social life cycle assessment of renewable electricity	Assessment of adverse social impacts of renewable electricity production	Generation of 1kWh 1 USD of generation cost	Cradle-to-gate	4	>15	Type I
Tan et al. (2023)	Assessing the Life Cycle Sustainability of Solar Energy Production Systems: A Toolkit Review in the Context of Ensuring Environmental Performance Improvements	Study of the status quo of the three pillars in the field of solar power generation	Unspecified	Cradle-to-grave	6	0	NS
Thornley et al. (2009)	Integrated assessment of bioelectricity technology options	Comparison of different bioenergy power generation systems	Generation of 1GWh	Cradle-to-grave	2	9	Type II
Tourinho et al. (2023)	Employment-Weighted Fair Wage Potential: A Social Indicator for the Power Sector	Proposition of an Employment-Weighted Fair Wage Potential (E-WFWP) indicator	Generation of 1 TWh	Cradle-to-grave	1	1	Type II
Traverso et al. (2012)	Towards life cycle sustainability assessment: An implementation to photovoltaic modules	LCSA of PV modules production and development of a Life Cycle Sustainability Dashboard	1 m² of PV modules	Cradle-to-gate	1	>15	Type I
Vogt Gwerder et al. (2019)	Life beyond the grid: A Life-Cycle Sustainability Assessment of household energy needs	LCSA of meeting electricity and heating needs in off-grid homes	The electricity (in kWh) and heat (in MJ) consumed by the household in order to satisfy its electricity and heating needs	Cradle-to-use	4	3	Type II
Volkart et al. (2016)	Interdisciplinary assessment of renewable, nuclear and fossil power generation with and	Evaluation of power supply options for Switzerland in 2035	Generation of 1kWh	Unspecified	-	6	Both

	without carbon capture and storage in view of the new Swiss energy policy						
Volkart et al. (2017)	Multi-criteria decision analysis of energy system transformation pathways: A case study for Switzerland	Energy system transformation pathways analysis, using the Swiss MARKAL Model method and scenario analysis	Unit of energy produced (e.g. MJ, TJ, PJ)	Unspecified	-	4	Both
W. Li et al. (2023)	Sustainability assessment of power generation systems under the objective consideration of criteria interactions	New MCDM framework to evaluate the sustainability of power generation systems	Generation of 1kWhGeneratio n of 1 TWh	Cradle-to-use	2	3	Both
Yilan et al. (2020)	Analysis of electricity generation options for sustainable energy decision making: The case of Turkey	Ranking of electricity generation technologies for Turkey according to their performance scores via MCDA	Generation of 1GWh	Cradle-to-grave	4	4	Both
Yu & Halog (2015)	Solar photovoltaic development in Australia - a life cycle sustainability assessment study	Case study to know whether current solar PV deployment is sustainable	Generation of 1kWh	Cradle-to-grave	8	>15	Type I
Zhang et al. (2021)	Environmental, social, and economic assessment of energy utilization of crop residue in China	Overview of the consequences of energy utilization of crop residues from a life cycle perspective	Unit of energy produced (e.g. MJ, TJ, PJ)	Cradle-to-grave	3	10	Type I

Both = Type I and Type II. NS = Not specified.

List of the multi-criteria decision analysis (MCDA) methods used in the reviewed literature

The predominant MCDA methods applied in the reviewed papers are Multi-Attribute Value Theory (MAVT, 09 occurrences), followed by Analytic Hierarchy Process (AHP, 08 occurrences), Weighted sum method (WSM, 05 occurrences), and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS, 03 occurrences). At lower frequency, with only 01 occurrence each, are: Compromise Programming (CP) method (Dorini et al., 2011); Data Envelopment Analysis (DEA) (Martín-Gamboa et al., 2022); Elimination and Choice Translating Reality (ELECTRE) IV partial aggregation outranking method (Genoud & Lesourd, 2009); Fuzzy Evaluation for Life Cycle Integrated Sustainability Assessment (FELICITA) model (Kouloumpis & Azapagic, 2018); Fuzzy interference system (Hemdi et al., 2013); Grey-Decision Making Trial and Evaluation Laboratory (G-DEMATEL) method (W. Li et al., 2023); interval Grey Relational Analysis (GRA) method (Ren, 2018); Multi-Attribute Utility Theory (MAUT) (Yilan et al., 2020); MIVES (Modelo Integrado de Valor para una Evaluación Sostenible or Integrated Value Model for Sustainability Assessment) method (Cartelle Barros et al., 2015); Preference Ranking Organization Method for Enrichment Evaluations (PROMETHEE) (Manzini Poli et al., 2022); adapted SWING method (Maxim, 2014); Vlsekriterijumska Optimizacijia I Kompromisno Resenje (VIKOR) method (W. Li et al., 2023); and Non-orthogonal coordinates based TOPSIS (NOC-TOPSIS) (Lin et al., 2022).

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Appendix B - Supplementary Material for Chapter 03

Table A1. Fair wage characterisation data

Country	RW (€)	MLW (€)	CWT (h)	RWT (h)	IEF	FWP
Construction & Decommissioning						
Germany	2,684.93	1,506.51	40	39	0.32	1.64
Brazil	446.75	423.33	44	43.7	0.53	0.76
China	261.21	311.14	44	48.2	0.47	0.6
Spain	1,953.47	600	40	37.8	0.35	3.03
USA	3,377.03	1,144.81	40	38.5	0.42	2.53
France	2,350.83	1,127.90	37.5	37.41	0.32	1.87
India	401.4	200.36	48	49	0.36	1.71
Italy	2,999.17	1,195.37	40	36.6	0.36	2.38
Japan	2,365.75	1,266.80	40	44.5	0.33	1.5
UK	3,115.38	1,256.39	44	43	0.35	2.23
Russia	334.89	347.98	40	35.5	0.37	0.94
Manufacturing						
Germany	3,381.73	1,506.51	40	38.4	0.32	2.09
Brazil	853.39	423.33	44	43.6	0.53	1.46
China	293.55	311.14	44	47.9	0.47	0.68
Spain	2,513.33	600	40	37.8	0.35	3.89
USA	2,740.85	1,144.81	40	40.8	0.42	1.93
France	2,714.83	1,127.90	37.5	37.35	0.32	2.16
India	655.27	200.36	48	47	0.36	2.91
Italy	3,464.06	1,195.37	40	35.9	0.36	2.81
Japan	2,191.70	1,266.80	40	42.4	0.33	1.46
UK	3,103.29	1,256.39	44	40.9	0.35	2.33
Russia	289.38	347.98	40	35.5	0.37	0.81
Fuel extraction and processing						
Germany - Agriculture	1,376.27	1,506.51	40	41.66	0.32	0.79
China - Mining	417.48	311.14	44	45.2	0.47	1.02
USA - Agriculture	1,714.00	1,144.81	40	42.3	0.42	1.17
USA - Mining	3,474.32	1,144.81	40	45.3	0.42	2.21
France - Mining	2,684.50	1,127.90	37.5	37.86	0.32	2.11
India - Mining	753.92	200.36	48	45.4	0.36	3.47
Italy - Agriculture	2,513.16	1,195.37	40	41	0.36	1.78
Japan - Mining	2,232.04	1,266.80	40	43.7	0.33	1.44
UK - Agriculture	2,220.09	1,256.39	44	43.9	0.35	1.55
Russia - Mining	598.7	347.98	40	35.5	0.37	1.68

Table A2. Companies' wage data

Power Technology	Company/sector	RW_n	MLW_n	CWT_n	RWT_n	IEF_n	FWP_n	Currency	Reference year
Solar PV	*China*								
	Xinyi Solar Holdings Ltd. (Xinyi Solar Holdings, 2016)	HK$7,627.32	HK$10,802.77 [1]	48.0	41.6	0.47	0.64	HKD	2019
	JA Solar (JA Solar Technology, 2020)	¥2,881.84	¥4,690.00	44.0	43.0	0.47	0.49	CNY	2019
	LONGi Solar (LONGi Green Energy Technology, 2019)	¥3,869.65	¥4,690.00	44.0	43.0	0.47	0.66	CNY	2019
	GCL-Poly Energy Holdings Ltd. (GCPEF) (GCL-Poly Energy Holdings, 2020)	¥13,080.23	¥4,690.00	44.0	43.0	0.47	2.24	CNY	2019
	Risen Energy (Risen Energy, 2020)	¥3,323.23	¥4,690.00	44.0	43.0	0.47	0.57	CNY	2019
	Japan								
	SB Energy (Soft Bank Group, n.d.)	¥167,983.99	¥157,325.60	40.0	41.0	0.33	0.93	JPY	2020
	ORIX Corporation (Orix Kabushiki Kaisha, 2021)	¥685,522.26	¥157,325.60	40.0	41.0	0.33	3.79	JPY	2020
	Mitsui & Co. (MITSUI, 2020)	¥1,161,176.42	¥157,325.60	40.0	41.0	0.33	6.42	JPY	2020
	Kyocera TLC Solar (KYOCERA, 2020)	¥596,546.92	¥157,325.60	40.0	41.0	0.33	3.30	JPY	2020
	USA								
	Solar sector (E2; ANCORE; CELI, 2020)	$ 24.48/h	$ 12,40/h	40.0	42.7	0.42	1.52	USD	2020
	India								
	Solar photovoltaic (PV) sector (Payscale, 2021n)	₹ 40,387.33	₹ 21,332.00	48.0	46.4	0.36	1.71	INR	2021

Hydro	*China*								
	Renewable energy power generation sector (Payscale, 2021l)	¥32,500.00	¥4,864.50	44.0	43.0	0.47	5.36	CNY	2021
	State Power Investment Corporation (SPIC) (SPIC, 2019)	¥11,032.60	¥4,690.00	44.0	43.0	0.47	1.89	CNY	2019
	State Development & Investment Corporation (SDIC) (SDIC Power Holdings, 2019)	¥9,796.50	¥4,255.00	44.0	43.0	0.47	1.85	CNY	2018
	India								
	Hydroelectric power generation sector (Payscale, 2021g)	₹ 68,970.75	₹ 21,332.00	48.0	46.4	0.36	2.91	INR	2021
	Brazil								
	Eletrobras (Eletrobras, 2020)	R$ 9,469.59	R$ 2,210.00	44.0	41.4	0.53	3.27	BRL	2019
	Norte Energia (Norte Energia, 2019)	R$ 15,759.64	R$ 2,210.00	44.0	41.4	0.53	5.44	BRL	2019
	Itaipu Binacional (Itaipu Binacional, 2019)	R$ 25,140.04	R$ 2,210.00	44.0	41.4	0.53	8.68	BRL	2019
	AES Tietê Energia S.A. (AES Tietê, 2020)	R$ 15,563.38	R$ 2,210.00	44.0	41.4	0.53	5.37	BRL	2019
Wind	*China*								
	Goldwind (Goldwind, 2020)	¥23,492.26	¥4,690.00	44.0	43.0	0.47	4.02	CNY	2019
	Dongfang Electric Corporation (Dongfang Electric Co. Ltd., 2020)	¥11,217.12	¥4,690.00	44.0	43.0	0.47	1.92	CNY	2019
	Sinovel Wind Power (Sinovel) (Sinovel Wind Power Technology, 2020)	¥17,092.54	¥4,690.00	44.0	43.0	0.47	2.92	CNY	2019
	USA								
	Wind power generation sector (Payscale, 2021o)	$6,361.33	$2,029.50	40.0	42.7	0.42	2.42	USD	2021
	Germany								

	Wind power generation sector (Payscale, 2021p)	€ 4,750.00	€ 1,806.50	40.0	38.2	0.32	2.46	EUR	2021
	India								
	Wind power generation sector (Payscale, 2021s)	₹ 45,833.33	₹ 21,332.00	48.0	46.4	0.36	1.94	INR	2021
	Spain								
	Wind power generation sector (Payscale, 2021q)	€ 2,333.33	€ 1,039.50	40.0	34.6	0.35	2.28	EUR	2021
	UK								
	Wind power generation sector (Payscale, 2021r)	£3,197.08	£1,164.50	44.0	39.7	0.35	2.67	GBP	2021
Oil	*China*								
	Oil and gas exploration sector (Payscale, 2021j)	¥25,208.33	¥4,864.50	44.0	43.0	0.47	4.16	CNY	2021
	Electric power distribution sector (Payscale, 2021d)	¥26,666.67	¥4,864.50	44.0	43.0	0.47	4.40	CNY	2021
	USA								
	Oil Sector	$5,572.90 [2]	$1,984.50	40.0	42.7	0.42	2.17	USD	2020
	Fossil fuel power generation sector (Payscale, 2021f)	$7,991.83	$2,029.50	40.0	42.7	0.42	3.04	USD	2021
	India								
	Fossil fuel power generation sector (Payscale, 2021e)	₹ 82,448.08	₹ 21,332.00	48.0	46.4	0.36	3.48	INR	2021
	Japan								
	Tokyo Electric Power Company (TEPCO) (TEPCO, 2020)	¥175,571.36	¥157,325.60	40.0	41.00	0.33	0.97	JPY	2020
	Russia								
	Unipro PJSC (Unipro PJSC, 2020)	95,965.10 ₽	21,311.50 ₽	40.0	35.5	0.37	4.39	RUB	2019

	Gazprom (Gazprom, 2019)	131,859.43 ₽	21,311.50 ₽	40.0	35.5	0.37	6.04	RUB	2019
	Inter RAO (Inter RAO UES, 2020)	95,646.05 ₽	21,311.50 ₽	40.0	35.5	0.37	4.38	RUB	2019
Gas	For the gas sector, the companies analysed were the same as those for the oil sector, differing only in the inclusion of the USA's sector:								
	Gas sector (E2; ANCORE; CELI, 2020)	$6,295.10 [2]	$1,984.50	40.0	42.7	0.42	2.45	USD	2020
Coal	*China*								
	Datang International power Generation (Datang International Power Generation, 2020)	¥15,551.01	¥4,690.00	44.0	43.0	0.47	2.66	CNY	2019
	Huadian Power International Corporation (Huadian Power International, 2019)	¥10,839.50	¥4,255.00	44.0	43.0	0.47	2.04	CNY	2018
	China Shenhua Energy (China Shenhua Energy, 2020)	¥17,174.69	¥4,690.00	44.0	43.0	0.47	2.94	CNY	2019
	USA								
	Coal Sector (E2; ANCORE; CELI, 2020)	$6,801.10	$1,984.50	40.0	42.7	0.42	2.65	USD	2020
	India								
	National Thermal Power Corporation Limited (NTPC) (National Thermal Power Corporation Limited (NTPC), 2019)	₹ 244,833.92	₹ 19,150.00	48.0	46.4	0.36	11.52	INR	2019
	Adani Power (Adani Power, 2021)	₹ 361,704.12	₹ 20,337.50	48.0	46.4	0.36	16.03	INR	2020
	Tata Power (Tata Power, 2020)	₹ 117,547.12	₹ 20,337.50	48.0	46.4	0.36	5.21	INR	2020
	Reliance Power (Reliance Power Ltd., 2019)	₹ 19,009.88	₹ 20,337.50	48.0	46.4	0.36	0.84	INR	2020
	NLC India Limited (NLC India Ltd, 2020)	₹ 160,290.19	₹ 20,337.50	48.0	46.4	0.36	7.10	INR	2020
Nuclear	*USA*								
	Nuclear sector (E2; ANCORE; CELI, 2020)	$9,016.00	$1,984.50	40.0	42.7	0.42	3.51	USD	2020
	Nuclear power generation sector (Payscale, 2021i)	$7,811.33	$2,029.50	40.0	42.7	0.42	2.97	USD	2021

	France								
	Nuclear power generation sector (Payscale, 2021h)	€ 3,498.00	€ 1,895.50	37.5	36.3	0.32	1.71	EUR	2021
	China								
	CLP Holdings (CLP Holdings, 2021)	HK$59,574.03	HK$11,111.73	48.0	43.0	0.47	4.69	HKD	2020
	China National Nuclear Power Co., Ltd. (CNNP) (China National Nuclear Power (CNNP), 2020)	¥18,787.60	¥4,690.00	44.0	43.0	0.47	3.21	CNY	2019
	China General Nuclear Power Group (CGN) (China General Nuclear Power Group (CGN), 2020)	¥6,463.64	¥4,690.00	44.0	43.0	0.47	1.11	CNY	2019
	Japan								
	KEPCO (Kansai Electric Power Company (KEPCO), 2019)	¥955,570.85	¥162,135.25	40.0	41.0	0.33	5.13	JPY	2019
Biomass-biogas	*Germany*								
	Envitec Biogas AG (Envitec Biogas AG, 2020)	€ 3,262.69	€ 1,760.00	40.0	38.2	0.32	1.74	EUR	2019
	USA								
	Animal waste biomethane gas collection sector (Payscale, 2021a)	$4,333.33	$2,029.50	40.0	42.7	0.42	1.65	USD	2021
	Biofuel power generation sector (Payscale, 2021b)	$5,553.25	$2,029.50	40.0	42.7	0.42	2.11	USD	2021
	UK								
	Biofuel power generation sector (Payscale, 2021c)	£2,254.00	£1,164.50	44.0	39.7	0.35	1.88	GBP	2021
	Italy								

Renewable power energy generation sector (Payscale, 2021m)	€ 3,211.17	€ 1,323.00	40.0	36.1	0.36	2.34	EUR	2021

[1] Estimated value: 2018 value plus 2019 inflation, obtained in: (World Bank, 2021)

[2] Table 3, page 13 of the reference. Weighted average between "Fossil Fuels" and "Fossil Fuel Generation": $24.23/hour. As the value per month was needed, this value was multiplied by 230h [the value obtained when dividing the annual salary on the payscale website by 12 (to become a monthly payment) and then dividing the found number by the value of the salary in hours to find the number of hours worked in a month]. Ex: annual salary: U$ 95,902.00 = Hourly wage: $34.76. Therefore, the number of hours is = 95,902.00/(12 x 34.76).

Table A3. Living wages of each analysed country at the considered year

Country	Living Wages			
	2018	2019	2020	2021
Germany (EUR/month)		1760.0		1806.5
Brazil (BRL/Month)		2210.0		
China (CNY/Month)	4255.0	4690.0	4807.0	4864.5
Spain (EUR/Month)				1039.5
USA (USD/Month)			1984.5	2029.5
France (EUR/Month)				1895.5
India (INR/Month)	18250.0	19150.0	20337.5	21332.0
Italy (EUR/Month)				1323.0
Japan (JPY/Month)		162135.2	157325.6	164527.8
United Kingdom (GBP/hour)				1164.5
Russia (RUB/Month)		21311.5		
Hong Kong (HKD/hour)	54.7	56.3	57.9	

Source: (Macrotrends, 2021; Oxfam Hong Kong, 2018; Statista, 2021a; The Living Wage Foundation, 2021; WageIndicator.org, 2021)

Table A4. Employment provided by different electricity options

Power technology	Employment (jobs-years/TWh)					
	Construction & installation	Manufacturing	O&M	Fuel extraction & processing	Decommissioning	Total Employment
Solar PV	197.87	101.98	319.63	0.00	39.57	659.06
Hydro (Reservoir)	7.22	3.41	29.27	0.00	1.44	41.35
Hydro (R-o-R)	27.49	18.97	682.15	0.00	5.50	734.11
Onshore wind	91.32	134.13	171.23	0.00	18.26	414.95

Offshore wind	152.21	296.80	76.10	0.00	30.44	555.56
Oil	12.37	8.85	39.95	77.40	2.47	141.04
Gas	13.02	9.31	42.06	81.47	2.60	148.46
Coal	116.76	56.30	43.79	395.51	23.35	635.70
Nuclear	41.89	4.61	85.19	1.00	8.38	141.07
Biomass-Biogas	193.72	40.13	518.89	326.18	38.74	1117.66

Appendix C - Supplementary Material for Chapter 04

1. Processes used for environmental assessment in SimaPro

2. Occupational accidents calculation

3. Gender equality

4. Proposed social, technical, and environmental impact categories/indicators

5. Results of the selected categories/indicators

6. Calculation of the normalised values

7. Calculation of the weighted normalised matrix

8. Power technology adequacy

9. References

1. Processes used for environmental assessment in SimaPro

Table S1. Processes selected for each technology in SimaPro

Technology	Processes
Solar PV	Electricity, low voltage {CN-BJ}| electricity production, photovoltaic, 570kWp open ground installation, multi-Si
	Electricity, low voltage {US-SERC}| electricity production, photovoltaic, 570kWp open ground installation, multi-Si
	Electricity, low voltage {JP}| electricity production, photovoltaic, 570kWp open ground installation, multi-Si
	Electricity, low voltage {DE}| electricity production, photovoltaic, 570kWp open ground installation, multi-Si
	Electricity, low voltage {IT}| electricity production, photovoltaic, 570kWp open ground installation, multi-Si
	Electricity, low voltage {AU}| electricity production, photovoltaic, 570kWp open ground installation, multi-Si
	Electricity, low voltage {KR}| electricity production, photovoltaic, 570kWp open ground installation, multi-Si
	Electricity, low voltage {ES}| electricity production, photovoltaic, 570kWp open ground installation, multi-Si
	Electricity, low voltage {RoW}| electricity production, photovoltaic, 570kWp open ground installation, multi-Si
Hydropower (Reservoir)	Electricity, high voltage {BR-Southern grid}| electricity production, hydro, reservoir, tropical region
	Electricity, high voltage {US-SERC}| electricity production, hydro, reservoir, non-alpine region
	Electricity, high voltage {CA-ON}| electricity production, hydro, reservoir, non-alpine region
	Electricity, high voltage {RU}| electricity production, hydro, reservoir, non-alpine region
	Electricity, high voltage {IN-PB}| electricity production, hydro, reservoir, alpine region
	Electricity, high voltage {NO}| electricity production, hydro, reservoir, alpine region
	Electricity, high voltage {TR}| electricity production, hydro, reservoir, non-alpine region
	Electricity, high voltage {JP}| electricity production, hydro, reservoir, alpine region
	Electricity, high voltage {FR}| electricity production, hydro, reservoir, alpine region
	Electricity, high voltage {RoW}| electricity production, hydro, reservoir, non-alpine region
Hydropower (R-o-R)	Electricity, high voltage {US-SERC}| electricity production, hydro, run-of-river
	Electricity, high voltage {CA-ON}| electricity production, hydro, run-of-river
	Electricity, high voltage {RU}| electricity production, hydro, run-of-river
	Electricity, high voltage {IN-PB}| electricity production, hydro, run-of-river
	Electricity, high voltage {TR}| electricity production, hydro, run-of-river
	Electricity, high voltage {JP}| electricity production, hydro, run-of-river
	Electricity, high voltage {FR}| electricity production, hydro, run-of-river
	Electricity, high voltage {RoW}| electricity production, hydro, run-of-river
Wind (Onshore)	Electricity, high voltage {CN-BJ}| electricity production, wind, >3MW turbine, onshore
	Electricity, high voltage {US-SERC}| electricity production, wind, >3MW turbine, onshore

	Electricity, high voltage {DE}| electricity production, wind, >3MW turbine, onshore Electricity, high voltage {IN-TN}| electricity production, wind, >3MW turbine, onshore Electricity, high voltage {RoW}| electricity production, wind, >3MW turbine, onshore
Wind (Offshore)	Electricity, high voltage {GB}| electricity production, wind, 1-3MW turbine, offshore Electricity, high voltage {CN-SH}| electricity production, wind, 1-3MW turbine, offshore Electricity, high voltage {DE}| electricity production, wind, 1-3MW turbine, offshore Electricity, high voltage {NL}| electricity production, wind, 1-3MW turbine, offshore Electricity, high voltage {RoW}| electricity production, wind, 1-3MW turbine, offshore
Oil	Electricity, high voltage {CN-BJ}| electricity production, oil Electricity, high voltage {US-SERC}| electricity production, oil Electricity, high voltage {IN-TN}| electricity production, oil Electricity, high voltage {JP}| electricity production, oil Electricity, high voltage {RU}| electricity production, oil Electricity, high voltage {RoW}| electricity production, oil
Gas	Electricity, high voltage {CN-BJ}| electricity production, natural gas, conventional power plant Electricity, high voltage {US-SERC}| electricity production, natural gas, conventional power plant Electricity, high voltage {IN-TN}| electricity production, natural gas, conventional power plant Electricity, high voltage {JP}| electricity production, natural gas, conventional power plant Electricity, high voltage {RU}| electricity production, natural gas, conventional power plant Electricity, high voltage {RoW}| electricity production, natural gas, conventional power plant
Coal	Electricity, high voltage {CN-BJ}| electricity production, hard coal Electricity, high voltage {US-SERC}| electricity production, hard coal Electricity, high voltage {IN-TN}| electricity production, hard coal Electricity, high voltage {RoW}| electricity production, hard coal
Nuclear	Electricity, high voltage {US-SERC}| electricity production, nuclear, pressure water reactor Electricity, high voltage {FR}| electricity production, nuclear, pressure water reactor Electricity, high voltage {CN-GD}| electricity production, nuclear, pressure water reactor Electricity, high voltage {JP}| electricity production, nuclear, pressure water reactor Electricity, high voltage {RoW}| electricity production, nuclear, pressure water reactor
Biogas	Electricity, high voltage {DE}| heat and power co-generation, biogas, gas engine Electricity, high voltage {US-SERC}| heat and power co-generation, biogas, gas engine Electricity, high voltage {GB}| heat and power co-generation, biogas, gas engine Electricity, high voltage {IT}| heat and power co-generation, biogas, gas engine Electricity, high voltage {TR}| heat and power co-generation, biogas, gas engine Electricity, high voltage {RoW}| heat and power co-generation, biogas, gas engine

2. Occupational accidents calculation

For the calculation of this indicator, the non-fatal occupational injuries per 100'000 workers by economic activity were obtained in the ILO website (ILO, 2024). The available data for most of the analysed countries, and the and reference year are presented below:

Table S2. Non-fatal occupational injuries per 100'000 workers by economic activity – Annual

Country	Installed Capacity	Construction	Manufacturing	Operation (Electricity; gas, steam and air conditioning supply)	Mining and quarrying	Reference Year
Solar PV						
China (Macao)[1]	36.0%	2342.3	2139.2	1166.7	1188.1	2016
USA	10.7%	1200	900	700	600	2018
Japan	9.5%	495	291	76	1080	2021
Germany	7.6%	4067	2144	656	2247	2022
Italy	3.1%	1934	1398.7	405.7	1198.2	2021
Australia	2.5%	1299.6	1293.1	816.3	921.4	2017
Republic of Korea	2.1%			No data		
Spain	2.0%	5364.9	3689.1	715.6	5106.9	2021
Reservoir						
Brazil[2]	9.5%	1374	1374	1374	1374	2017
USA	7.3%	1200	900	700	600	2018
Canada	7.0%			No data		
Russian Federation	4.4%			No data		
India	4.0%			No data		
Norway	2.9%	156.6	108.6	45.6	40.8	2022
Turkey	2.7%			No data		
Japan	2.4%	495	291	76	1080	2021
France	2.1%	5997.7	2751.1	311.1	2017.6	2021
R-o-R						
USA	7.3%	1200	900	700	600	2018
Canada	7.0%			No data		
Russian Federation	4.4%			No data		
India	4.0%			No data		
Turkey	2.7%			No data		
Japan	2.4%	495	291	76	1080	2021
France	2.1%	5997.7	2751.1	311.1	2017.6	2021
Onshore Wind						
China (Macao)	46.4%	2342.3	2139.2	1166.7	1188.1	2016
USA	20.0%	1200	900	700	600	2018

Country	Installed Capacity	Construction	Manufacturing	Operation (Electricity; gas, steam and air conditioning supply)	Mining and quarrying	Reference Year
Germany	9.3%	4067	2144	656	2247	2022
India	6.6%	No data				
Offshore Wind						
United Kingdom	30%	982	1132.1	235.9	300.1	2018
China (Macao)	26%	2342.3	2139.2	1166.7	1188.1	2016
Germany	23%	4067	2144	656	2247	2022
Netherlands	7%	1168.8	1477.9	696.4	1200.1	2021
Oil						
China (Macao)	28.2%	2342.3	2139.2	1166.7	1188.1	2016
USA	16.2%	1200	900	700	600	2018
India	7.4%	No data				
Japan	4.9%	495	291	76	1080	2021
Russian Federation	4.2%	No data				
Gas						
China (Macao)	28.2%	2342.3	2139.2	1166.7	1188.1	2016
USA	16.2%	1200	900	700	600	2018
India	7.4%	No data				
Japan	4.9%	495	291	76	1080	2021
Russian Federation	4.2%	No data				
Coal						
China (Macao)	50%	2342.3	2139.2	1166.7	1188.1	2016
USA	13%	1200	900	700	600	2018
India	11%	No data				
Nuclear						
USA	25.0%	1200	900	700	600	2018
France	16.1%	5997.7	2751.1	311.1	2017.6	2021
China (Macao)	11.6%	2342.3	2139.2	1166.7	1188.1	2016
Japan	8.1%	495	291	76	1080	2021
Biogas						
Germany	37.0%	4067	2144	656	2247	2022
USA	11.4%	1200	900	700	600	2018
United Kingdom	9.2%	982	1132.1	235.9	300.1	2018
Italy	7.1%	1934	1398.7	405.7	1198.2	2021
Turkey	3.7%	No data				

[1] There was no Mining activity for China, but considering its importance, and high weight in several non-renewable technologies, we adopted and aggregated value: Hong Kong, ChinaADM-LIR - Labour Inspectorate RecordsAggregate: Total (2016)

[2] There is no division by economic activity, so the aggregated value was adopted.

When calculating jobs creation, Atilgan & Azapagic (2016) considered that the decommissioning stage employs 20% of the number of workers in the construction stage. The same principle is adopted in the present work, i.e., the decommissioning stage assume 20% of the non-fatal injuries observed by the construction stage.

When no data was found for a specific country, its weight was redistributed proportionally for the other countries with existing data, considering the proportional installed capacity.

3. Gender equality

This section presents the rate of female workforce of each technology, or analysed company with available data:

2.1. Gender equality data was used for each power technology whenever available. When publications with global values for a given technology were not found, the following methodology was applied:

- Checking the main countries with installed capacity of the analysed technology.
- In the chosen countries, look for companies that present a significant portion of their electricity generation portfolio in the form of the studied technology.
- Search, in the available reports of each company (Annual / Financial / Consolidated / Corporate Responsibility), gender equality data. The most recent published reports at the time of the research were considered.
- Calculate the average of the values found within the same country.
- Calculate the weighted average between countries and extrapolate this value to the rest of the world. The result will be considered the world female workforce on the selected technology.

Share of women employed in each power technology sector:

- Solar PV technology: 40% (IRENA, 2022).
- Hydropower: 25% (Energy Sector Management Assistance Program (ESMAP), 2023).
- Wind power: 21% (IRENA, 2022).
- Oil & gas power: 22% (IRENA, 2022).
- Nuclear power: 24.9% (NEA, 2023).

2.2. Considering the coal-fired power, the following assumptions were made:

The three main countries that together account for approximately 75% of the installed capacity of this technology are: China (50.1%), USA (13.2%) and India (11.4%) (Tourinho et al., 2023). In this case, the female presence in the coal production chain was additionally considered.

Although China has the largest share of installed capacity, the official percentage of women working in coal mines is zero, as article 59 of the labor legislation of the People's Republic of China does not allow women to work in underground mining (The National People’s Congress of the People’s Republic of China, 1995). Furthermore, no reports from Chinese companies were found presenting female workforce percentages on this power technology, which is why it was considered that, for China, this value would be equal to zero.

According to (Potter & Kuykendall (2019), in USA women accounted for 4.4% of the coal mining sector's workforce in 2018. While for India, women comprise 48% of the workforce in coal mines (Park et al., 2019).

Considering the values found for these countries, and installed capacity proportion presented in Table 4.1, a weighted average of 8.1% was obtained for positions held by women in this technology (Table S2):

Table S3. Data for the calculation of women workforce in coal-fired power

Main countries presenting the technology	World's installed capacity	Proportional value	Women in workforce	Weighted average
China	50.1%	67.1%	0%	0%
EUA	13.2%	17.6%	4.4%	0.8%
India	11.4%	15.3%	48%	7.3%
total	75%	100.0%		**8.1%**

2.3. Considering the biogas power, the following assumptions were made:

The main countries that, together, account for approximately 65% of the installed capacity of this technology are: Germany (37.0%), USA (11.4%), United Kingdom (9.2%) and Italy (7.1%) (Tourinho et al., 2023).

It is worth mentioning that among the technologies considered in the present study, Biogas presents smaller companies, compared to the other power technologies, both in financial terms and installed capacity. In this sense, it is more difficult to find reports that present gender issues in their content. Some of the data were obtained through electronic mail consultation in 2021.

The companies analysed are presented below (Table S3):

Table S4. Women workforce rate in the analysed biomass power companies

Country	Company	Women workforce rate	Year	Reference
Germany	Verbio (Biofuel and Technology)	19.3%	2023	(VERBIO, 2023)
USA	Bright Biomethane North America Inc.	14.0%	2021	e-mail
	AB Energy USA	25.0%	2021	e-mail
United Kingdom	Ramboll Group A/S	34.6%	2021	e-mail
	Energia Group	45.0%	2022	(ENERGIA GROUP Ltd., 2022)
Italy	SNAM	15.6%	2021	(SNAM, 2021)

After analysing the reports made available by companies whose headquarters were in the aforementioned countries, or questionnaire by e-mail, it was observed through a weighted average that the proportion of women workforce in these countries for the biomass technology was 21.8% (Table S4):

Table S5. Data for the calculation of women workforce in biomass power

Main countries presenting the technology	World's installed capacity	Proportional value	Women in workforce	Weighted average
Germany	37.0%	57.2%	19.3%	11.0%
USA	11.4%	17.6%	19.5%	3.4%
United Kingdom	9.2%	14.2%	40%	5.7%
Italy	7.1%	11.0%	15.6%	1.7%
Total	64.7%	100.0%	-	**21.8%**

4. Proposed social, technical, and environmental impact categories/indicators

Table S6 presents the suggested impact categories/indicators for the proposed framework, considering the SDGs' targets and indicators available in United Nations (2024).

5. Results of the selected categories/indicators

Table S7 presents the results of the selected categories/indicators for each power technology.

6. Calculation of the normalised values

Table S8 presents the normalised results matrix of the social, technical and environmental impact category/indicator values for each electricity option, ranging from 0.00 to 1.00.

7. Calculation of the weighted normalised matrix

Table S9 shows the normalised results from social, technical and environmental LCA for each power option in each SDG, ranging from 0 to 100.

8. Power technology adequacy

Table S10 presents the Power technology score considering the company's focused SDGs.

Table S6: Selected social, technical, and environmental indicators and their association with the SDGs' targets

SDG	SDG' Target	SDG indicator	Proposed impact categories/indicators	Reference
SDG 1: No poverty	1.1 By 2030, eradicate extreme poverty for all people everywhere, currently measured as people living on less than $1.25 a day	1.1.1 Proportion of the population living below the international poverty line by sex, age, employment status and geographical location (urban/rural)	Total employment	Tourinho et al. (2023)
	1.2 By 2030, reduce at least by half the proportion of men, women and children of all ages living in poverty in all its dimensions according to national definitions	1.2.1 Proportion of population living below the national poverty line, by sex and age	E-WFWP	Tourinho et al. (2023)
SDG 2: Zero Hunger	2.4 By 2030, ensure sustainable food production systems and implement resilient agricultural practices that increase productivity and production, that help maintain ecosystems, that strengthen capacity for adaptation to climate change, extreme weather, drought, flooding and other disasters and that progressively improve land and soil quality	2.4.1 Proportion of agricultural area under productive and sustainable agriculture	Terrestrial acidification	ReCiPe 2016 Midpoint (H) V1.08
			Terrestrial ecotoxicity	ReCiPe 2016 Midpoint (H) V1.08
			Land use	ReCiPe 2016 Midpoint (H) V1.08
SDG 3: Good Health and Well-Being	3.4 By 2030, reduce by one third premature mortality from non-communicable diseases through prevention and treatment and promote mental health and well-being	3.4.1 Mortality rate attributed to cardiovascular disease, cancer, diabetes or chronic respiratory disease	Human carcinogenic toxicity	ReCiPe 2016 Midpoint (H) V1.08
	3.9 By 2030, substantially reduce the number of deaths and illnesses from hazardous chemicals and air, water and soil pollution and contamination	3.9.1 Mortality rate attributed to household and ambient air pollution	Human non-carcinogenic toxicity	ReCiPe 2016 Midpoint (H) V1.08
			Fine particulate matter formation	ReCiPe 2016 Midpoint (H) V1.08

		3.9.1 Mortality rate attributed to household and ambient air pollution 3.9.2 Mortality rate attributed to unsafe water, unsafe sanitation and lack of hygiene (exposure to unsafe Water, Sanitation and Hygiene for All (WASH) services) 3.9.3 Mortality rate attributed to unintentional poisoning	Fatalities	Our World in Data (2021)
SDG 4: Quality education			-	-
SDG 5: Gender equality	5.1 End all forms of discrimination against all women and girls everywhere	5.1.1 Whether or not legal frameworks are in place to promote, enforce and monitor equality and non-discrimination on the basis of sex	Gender equality	Present study
SDG 6: Clean Water and Sanitation	6.3 By 2030, improve water quality by reducing pollution, eliminating dumping and minimizing release of hazardous chemicals and materials, halving the proportion of untreated wastewater and substantially increasing recycling and safe reuse globally	6.3.2 Proportion of bodies of water with good ambient water quality	Freshwater ecotoxicity	ReCiPe 2016 Midpoint (H) V1.08
			Freshwater eutrophication	ReCiPe 2016 Midpoint (H) V1.08
	6.4 By 2030, substantially increase water-use efficiency across all sectors and ensure sustainable withdrawals and supply of freshwater to address water scarcity and substantially reduce the number of people suffering from water scarcity	6.4.2 Level of water stress: freshwater withdrawal as a proportion of available freshwater resources	Water use	AWARE V1.05 (Available WAter REmaining)
SDG 7: Affordable and Clean Energy	7.1 By 2030, ensure universal access to affordable, reliable and modern energy services	7.1.1 Proportion of population with access to electricity	Microgrid Generation Option	Present study, based on Hirsch et al. (2018), Sarkar

				(2021), and Lambert et al. (2006)
	7.2 By 2030, increase substantially the share of renewable energy in the global energy mix	7.2.1 Renewable energy share in the total final energy consumption	Non-renewable energy	Cumulative Energy Demand V1.11
	7.3 By 2030, double the global rate of improvement in energy efficiency	7.3.1 Energy intensity measured in terms of primary energy and GDP	Fossil resource scarcity	ReCiPe 2016 Midpoint (H) V1.08
			EROI	Present study, based on Weißbach et al. (2013), Dale & Bodger (2012), Trainer (2018), Jain et al. (2020)
SDG 8: Decent work and economic growth	8.3 Promote development-oriented policies that support productive activities, decent job creation, entrepreneurship, creativity and innovation, and encourage the formalization and growth of micro-, small- and medium-sized enterprises, including through access to financial services	8.3.1 Proportion of informal employment in total employment, by sector and sex	Direct Employment	Tourinho et al. (2023)
			Total Employment	Tourinho et al. (2023)
	8.5 By 2030, achieve full and productive employment and decent work for all women and men, including for young people and persons with disabilities, and equal pay for work of equal value	8.5.1 Average hourly earnings of female and male employees, by occupation, age and persons with disabilities	E-WFWP	Tourinho et al. (2023)
	8.8 Protect labour rights and promote safe and secure working environments for all workers, including migrant workers, in particular women migrants, and those in precarious employment	8.8.1 Fatal and non-fatal occupational injuries per 100,000 workers, by sex and migrant status	Occupational accidents	Present study
			Fatalities	Our World in Data (2021)

SDG 9: Industry, innovation and infrastructure	9.1 Develop quality, reliable, sustainable and resilient infrastructure, including regional and transborder infrastructure, to support economic development and human well-being, **with a focus on affordable and equitable access for all**	9.1.1 Proportion of the rural population who live within 2 km of an all-season road	Microgrid Generation Option	Present study, based on Hirsch et al. (2018), Sarkar (2021), and Lambert et al. (2006)
	9.2 Promote inclusive and sustainable industrialization and, by 2030, significantly raise industry's share of employment and gross domestic product, in line with national circumstances, and double its share in least developed countries	9.2.2 Manufacturing employment as a proportion of total employment	Manufacturing employment rate	Present study based on Tourinho et al. (2023)
	9.4 By 2030, upgrade infrastructure and retrofit industries to make them sustainable, **with increased resource-use efficiency and greater adoption of clean and environmentally sound technologies and industrial processes**, with all countries taking action in accordance with their respective capabilities	9.4.1 CO2 emission per unit of value added	Average Dissipation Rate (ADR)	Mineral resource dissipation (Charpentier Poncelet et al., 2022)
			Lost Potential Service Time (LPST)	Mineral resource dissipation (Charpentier Poncelet et al., 2022)
			Mineral resource scarcity	ReCiPe 2016 Midpoint (H) V1.08
			Fossil resource scarcity	ReCiPe 2016 Midpoint (H) V1.08
SDG 10: Reduced inequalities	10.1 By 2030, progressively achieve and sustain income growth of the bottom 40 per cent of the population at a rate higher than the national average	10.1.1 Growth rates of household expenditure or income per capita among the bottom 40 per cent of the population and the total population	E-WFWP	Tourinho et al. (2023)

SDG 11: Sustainable Cities and Communities	11.6 By 2030, reduce the adverse per capita environmental impact of cities, including by paying special attention to air quality and municipal and other waste management	11.6.2 Annual mean levels of fine particulate matter (e.g. PM2.5 and PM10) in cities (population weighted)	Fine particulate matter formation	ReCiPe 2016 Midpoint (H) V1.08
			Photochemical oxidantion (kg NMVOC)	EPD (2018)
		11.6.1 Proportion of municipal solid waste collected and managed in controlled facilities out of total municipal waste generated, by cities	Waste, non-radioactive	Ecological Scarcity 2021
			Radioactive waste to deposit	Ecological Scarcity 2021
SDG 12: Responsible Consumption and Production	12.2 By 2030, achieve the sustainable management and efficient use of natural resources	12.2.1 Material footprint, material footprint per capita, and material footprint per GDP	Resource use, minerals and metals	EN 15804 +A2 Method
			Mineral resource scarcity	ReCiPe 2016 Midpoint (H) V1.08
			Average Dissipation Rate (ADR)	Mineral resource dissipation (Charpentier Poncelet et al., 2022)
			Lost Potential Service Time (LPST)	Mineral resource dissipation (Charpentier Poncelet et al., 2022)
	12.4 By 2020, achieve the environmentally sound management of chemicals and all wastes throughout their life cycle, in accordance with agreed international frameworks, and significantly reduce their release to air, water and soil in order to minimize their adverse impacts on human health and the environment	12.4.2 (a) Hazardous waste generated per capita; and (b) proportion of hazardous waste treated, by type of treatment	Radioactive waste to deposit	Ecological Scarcity 2021

	12.5 By 2030, substantially reduce waste generation through prevention, reduction, recycling and reuse	12.5.1 National recycling rate, tons of material recycled	Waste, non-radioactive	Ecological Scarcity 2021
SDG 13: Climate Action	13.2 Integrate climate change measures into national policies, strategies and planning	13.2.2 Total greenhouse gas emissions per year	Climate change	IPCC 2021 GWP100
SDG 14: Life Below Water	14.1 By 2025, prevent and significantly reduce marine pollution of all kinds, in particular from land-based activities, including marine debris and nutrient pollution	14.1.1 (a) Index of coastal eutrophication; and (b) plastic debris density	Marine eutrophication	ReCiPe 2016 Midpoint (H) V1.08
			Marine ecotoxicity	ReCiPe 2016 Midpoint (H) V1.08
	14.3 Minimize and address the impacts of ocean acidification, including through enhanced scientific cooperation at all levels	14.3.1 Average marine acidity (pH) measured at agreed suite of representative sampling stations	Marine acidification, short term	IMPACT World+ Endpoint
SDG 15: Life on Land	15.5 Take urgent and significant action to reduce the degradation of natural habitats, halt the loss of biodiversity and, by 2020, protect and prevent the extinction of threatened species	15.5.1 Red List Index	Ecosystems (species.yr)	ReCiPe 2016 Endpoint (H) V1.08
			Potential Species Loss from Land Use (PSL) - Global	Land use impacts on biodiversity ((Chaudhary et al., 2015)
	15.3 By 2030, combat desertification, restore degraded land and soil, including land affected by desertification, drought and floods, and strive to achieve a land degradation-neutral world	15.3.1 Proportion of land that is degraded over total land area	Land use	ReCiPe 2016 Midpoint (H) V1.08
			Terrestrial acidification	ReCiPe 2016 Midpoint (H) V1.08
			Terrestrial ecotoxicity	ReCiPe 2016 Midpoint (H) V1.08

SDG 16: Peace, Justice and Strong Institutions	16.b Promote and enforce non-discriminatory laws and policies for sustainable development	16.b.1 Proportion of population reporting having personally felt discriminated against or harassed in the previous 12 months on the basis of a ground of discrimination prohibited under international human rights law	Gender Equality	Present study

Table S7. Results of the selected categories/indicators for each power technology

Dimension	Impact categories / indicators	Unit	Solar PV	Reservoir	R-o-R	Wind - onshore	Wind - offshore	Oil	Gas	Coal	Nuclear	Biogas
Social	Direct Employment	jobs-years/kWh	1.04E-06	8.20E-08	1.62E-06	2.23E-07	2.68E-07	6.50E-08	5.40E-08	1.26E-07	1.30E-07	4.97E-07
	Manufacturing employment rate	%	15.5%	8.3%	2.6%	32.3%	53.4%	6.3%	6.3%	8.9%	3.3%	3.6%
	Total Employment	jobs-years/kWh	1.23E-06	8.93E-08	1.67E-06	3.30E-07	5.76E-07	1.67E-07	1.39E-07	4.37E-07	1.36E-07	7.40E-07
	Occupational accidents	Injuries/kWh	1.8E-08	8.6E-10	9.7E-09	5.2E-09	1.0E-08	1.8E-09	1.5E-09	6.0E-09	1.8E-09	1.0E-08
	Fatalities	Fatalities/kWh	1.90E-11	1.30E-09	1.30E-09	3.50E-11	3.50E-11	1.84E-08	2.82E-09	2.46E-08	3.00E-11	4.63E-09
	Gender Equality	%	10.0%	25.0%	25.0%	29.0%	29.0%	28.0%	28.0%	41.9%	25.1%	28.2%
	E-WFWP	-	1.16	2.80	3.33	1.97	1.66	2.16	2.17	1.59	2.56	1.66
Technical	Energy return on investment (EROI)	-	6.90	62.50	62.50	20.48	20.48	16.00	37.33	23.00	32.33	8.38
	Microgrid Generation Option (MGO)	-	1	0	1	1	0	0	1	0	0	1
Environmental	Fine particulate matter formation	kg PM2.5 eq/kWh	1.69E-04	9.92E-06	9.30E-06	4.02E-05	3.63E-05	2.08E-03	8.66E-05	2.29E-03	2.77E-05	3.33E-04
	Terrestrial acidification	kg SO2 eq/kWh	3.54E-04	1.63E-05	1.37E-05	7.71E-05	7.04E-05	6.59E-03	2.18E-04	5.54E-03	3.51E-05	1.31E-03
	Freshwater eutrophication	kg P eq/kWh	4.40E-05	1.41E-06	1.17E-06	1.08E-05	8.01E-06	1.56E-05	7.18E-06	3.90E-04	4.28E-06	4.34E-05
	Marine eutrophication	kg N eq/kWh	3.99E-06	1.30E-07	1.03E-07	1.20E-06	1.32E-06	1.82E-05	9.22E-07	2.52E-05	1.28E-05	3.05E-06

Terrestrial ecotoxicity	kg 1,4-DCB/kWh	2.00E+00	2.83E-02	2.09E-02	2.70E-01	3.08E-01	3.89E+00	9.23E-02	5.93E-01	2.46E-01	3.08E-01
Freshwater ecotoxicity	kg 1,4-DCB/kWh	1.73E-02	2.52E-04	3.01E-04	8.42E-03	4.58E-03	2.80E-03	1.11E-03	1.46E-02	1.13E-03	3.96E-03
Marine ecotoxicity	kg 1,4-DCB/kWh	2.28E-02	3.43E-04	3.96E-04	1.04E-02	5.81E-03	6.62E-03	1.54E-03	2.04E-02	1.59E-03	5.24E-03
Human carcinogenic toxicity	kg 1,4-DCB/kWh	1.39E-02	1.83E-03	1.87E-03	1.41E-02	1.19E-02	1.09E-02	6.58E-03	4.12E-02	2.97E-03	7.11E-03
Human non-carcinogenic toxicity	kg 1,4-DCB/kWh	2.04E-01	4.89E-03	3.49E-03	4.66E-02	4.64E-02	9.76E-02	2.05E-02	6.91E-01	8.85E-02	1.03E-01
Land use	m2a crop eq/kWh	2.90E-02	5.38E-03	2.63E-04	1.38E-03	3.88E-04	5.79E-03	2.14E-03	1.24E-02	2.67E-04	8.57E-03
Fossil resource scarcity	kg oil eq/kWh	2.05E-02	1.13E-03	9.14E-04	5.21E-03	3.98E-03	2.92E-01	1.97E-01	2.46E-01	1.83E-03	2.34E-02
Mineral resource scarcity	kg Cu eq/kWh	1.06E-03	9.19E-05	8.24E-05	5.98E-04	5.93E-04	4.30E-04	3.13E-04	3.10E-04	7.04E-04	3.51E-04
Lost potential service time (LPST)100	kg Fe-eq/kWh	6.11E-03	5.66E-04	6.90E-04	4.65E-03	3.57E-03	1.03E-02	7.36E-03	3.17E-03	5.27E-04	2.11E-03
average dissipation rate (ADR)	kg Fe-eq/kWh	1.22E-02	9.45E-04	1.00E-03	6.46E-03	5.30E-03	1.17E-01	7.92E-02	7.24E-03	1.22E-03	5.14E-03
Water use	m3/kWh	7.85E-02	9.57E-01	1.42E-03	5.43E-03	7.28E-03	6.64E-02	1.24E-02	6.41E-02	9.53E-02	8.34E-03
Non-renewable, fossil	MJ/kWh	9.43E-01	5.17E-02	4.20E-02	2.39E-01	1.82E-01	1.34E+01	9.00E+00	1.14E+01	8.41E-02	1.08E+00
Non-renewable, nuclear	MJ/kWh	1.06E-01	4.57E-03	1.94E-03	1.77E-02	1.56E-02	3.97E-02	1.44E-02	2.99E-02	1.33E+01	6.15E-02
Non-renewable, biomass	MJ/kWh	6.43E-05	6.90E-06	5.62E-06	2.06E-05	1.91E-05	4.26E-05	3.45E-05	5.20E-05	4.16E-06	8.56E-05
Photochemical oxidation	kg NMVOC/kWh	3.46E-04	3.55E-05	2.34E-05	9.53E-05	7.09E-05	5.18E-03	1.05E-03	3.54E-03	4.68E-05	7.36E-04
Waste, non-radioactive	UBP/kWh	1.07E+01	6.40E-02	5.74E-02	2.08E+00	1.05E+00	9.76E+00	5.91E+00	1.11E+00	2.37E-01	1.93E+00
Radioactive waste to deposit	UBP/kWh	3.87E+00	1.62E-01	8.16E-02	5.85E-01	4.39E-01	1.85E+00	5.23E-01	1.32E+00	3.30E+02	2.27E+00
Resource use, minerals and metals	kg Sb eq/kWh	3.35E-06	2.68E-08	2.38E-08	5.49E-07	5.90E-07	2.19E-07	1.37E-07	2.24E-07	1.23E-07	4.04E-07
GWP100 - fossil	kg CO2-eq/kWh	8.00E-02	6.21E-03	4.56E-03	1.91E-02	1.62E-02	1.04E+00	5.05E-01	1.09E+00	6.80E-03	1.29E-01
Marine acidification, short term	PDF.m2.yr/kWh	1.16E-03	4.72E-04	6.98E-05	2.82E-04	2.41E-04	1.59E-02	7.57E-03	1.63E-02	1.01E-04	1.64E-03
Ecosystems	species.yr/kWh	6.84E-10	4.91E-10	2.22E-11	1.10E-10	8.57E-11	4.98E-09	1.59E-09	5.10E-09	6.34E-11	1.15E-09
PSLglo Occupation	PDF.year/kWh	9.68E-17	4.48E-19	5.92E-19	4.70E-18	1.29E-18	6.99E-18	1.65E-18	4.26E-17	8.86E-19	2.94E-17
PSLglo Transformation	PDF.year//kWh	-1.81E-16	6.58E-17	5.07E-18	-3.08E-18	-2.62E-19	-2.46E-17	-9.89E-18	-2.89E-18	-1.92E-19	-9.66E-18

Table S8. Normalized matrix of impact categories with statistical analysis

Impact categories	Power Technologies										Statistics			
	Solar PV	Reservoir	R-o-R	Wind - onshore	Wind - offshore	Oil	Gas	Coal	Nuclear	Biogas	Mean (μ)	Standard deviation (σ)	μ-σ	μ+σ
Direct Employment	0.625	0.018	1.000	0.108	0.136	0.007	0.000	0.046	0.049	0.282	0.227	0.315	-0.087	0.542
Manufacturing employment rate	0.254	0.112	0.000	0.585	1.000	0.073	0.073	0.123	0.014	0.020	0.225	0.306	-0.081	0.531
Total Employment	0.720	0.000	1.000	0.152	0.308	0.049	0.031	0.220	0.029	0.412	0.292	0.317	-0.025	0.609
Occupational accidents	0.000	1.000	0.474	0.740	0.452	0.943	0.962	0.695	0.942	0.440	0.665	0.306	0.359	0.971
Fatalities	1.000	0.948	0.948	0.999	0.999	0.252	0.886	0.000	1.000	0.813	0.784	0.339	0.445	1.123
Gender equality	1.000	0.530	0.530	0.404	0.404	0.436	0.436	0.000	0.526	0.431	0.470	0.229	0.241	0.699
E-WFWP	0.000	0.759	1.000	0.375	0.231	0.463	0.468	0.199	0.648	0.233	0.438	0.283	0.154	0.721
Energy return on investment (EROI)	0.110	1.000	1.000	0.328	0.328	0.256	0.597	0.368	0.517	0.134	0.464	0.303	0.161	0.767
Microgrid Generation Option (MGO)	1.000	0.000	1.000	1.000	0.000	0.000	1.000	0.000	0.000	1.000	0.500	0.500	0.000	1.000
Fine particulate matter formation	0.930	1.000	1.000	0.986	0.988	0.094	0.966	0.000	0.992	0.858	0.782	0.370	0.412	1.152
Terrestrial acidification	0.948	1.000	1.000	0.990	0.991	0.000	0.969	0.159	0.997	0.803	0.786	0.359	0.427	1.145
Freshwater eutrophication	0.890	0.999	1.000	0.975	0.982	0.963	0.985	0.000	0.992	0.892	0.868	0.292	0.576	1.160
Marine eutrophication	0.845	0.999	1.000	0.956	0.952	0.280	0.967	0.000	0.495	0.882	0.738	0.336	0.402	1.074
Terrestrial ecotoxicity	0.488	0.998	1.000	0.936	0.926	0.000	0.982	0.852	0.942	0.926	0.805	0.304	0.501	1.109
Freshwater ecotoxicity	0.000	1.000	0.997	0.521	0.747	0.851	0.950	0.160	0.948	0.783	0.696	0.339	0.357	1.034
Marine ecotoxicity	0.000	1.000	0.998	0.551	0.756	0.720	0.947	0.108	0.945	0.782	0.681	0.342	0.339	1.022
Human carcinogenic toxicity	0.694	1.000	0.999	0.690	0.745	0.770	0.879	0.000	0.971	0.866	0.761	0.278	0.484	1.039
Human non-carcinogenic toxicity	0.708	0.998	1.000	0.937	0.938	0.863	0.975	0.000	0.876	0.855	0.815	0.284	0.531	1.099
Land use	0.000	0.822	1.000	0.961	0.996	0.808	0.935	0.578	1.000	0.711	0.781	0.293	0.488	1.074
Fossil resource scarcity	0.933	0.999	1.000	0.985	0.989	0.000	0.324	0.157	0.997	0.923	0.731	0.381	0.349	1.112
Mineral resource scarcity	0.000	0.990	1.000	0.474	0.480	0.646	0.765	0.768	0.366	0.727	0.622	0.287	0.334	0.909
Lost potential service time (LPST)	0.430	0.996	0.983	0.579	0.690	0.000	0.303	0.730	1.000	0.839	0.655	0.315	0.340	0.970
average dissipation rate (ADR)	0.903	1.000	1.000	0.952	0.962	0.000	0.326	0.946	0.998	0.964	0.805	0.330	0.475	1.135
Water use	0.919	0.000	1.000	0.996	0.994	0.932	0.989	0.934	0.902	0.993	0.866	0.291	0.575	1.157
Non-renewable, fossil	0.932	0.999	1.000	0.985	0.989	0.000	0.327	0.148	0.997	0.922	0.730	0.382	0.348	1.112
Non-renewable, nuclear	0.992	1.000	1.000	0.999	0.999	0.997	0.999	0.998	0.000	0.996	0.898	0.299	0.599	1.197
Non-renewable, biomass	0.262	0.966	0.982	0.799	0.817	0.529	0.627	0.412	1.000	0.000	0.639	0.320	0.319	0.960
Photochemical oxidation	0.937	0.998	1.000	0.986	0.991	0.000	0.802	0.319	0.995	0.862	0.789	0.329	0.460	1.118
Waste, non-radioactive	0.000	0.999	1.000	0.810	0.907	0.086	0.449	0.901	0.983	0.824	0.696	0.361	0.335	1.056

Radioactive waste to deposit	0.989	1.000	1.000	0.998	0.999	0.995	0.999	0.996	0.000	0.993	0.897	0.299	0.598	1.196
Resource use, minerals and metals	0.000	0.999	1.000	0.842	0.830	0.941	0.966	0.940	0.970	0.886	0.837	0.285	0.552	1.122
GWP100 - fossil	0.931	0.998	1.000	0.987	0.989	0.046	0.540	0.000	0.998	0.885	0.737	0.381	0.357	1.118
Marine acidification, short term	0.933	0.975	1.000	0.987	0.989	0.026	0.538	0.000	0.998	0.903	0.735	0.384	0.351	1.119
Ecosystems	0.870	0.908	1.000	0.983	0.987	0.023	0.692	0.000	0.992	0.779	0.723	0.369	0.355	1.092
PSLglo Occupation	0.000	1.000	0.999	0.956	0.991	0.932	0.988	0.563	0.995	0.699	0.812	0.306	0.506	1.118
PSLglo Transformation	1.000	0.000	0.246	0.279	0.267	0.366	0.306	0.278	0.267	0.305	0.332	0.241	0.091	0.572

Table S9. SDGs weighted normalized matrix

SDGs	Solar PV	Reservoir	R-o-R	Wind - onshore	Wind - offshore	Oil	Gas	Coal	Nuclear	Biogas
SDG 1: No poverty	0.36	0.38	1.00	0.26	0.27	0.26	0.25	0.21	0.34	0.32
SDG 2: Zero Hunger	0.48	0.94	1.00	0.96	0.97	0.27	0.96	0.53	0.98	0.81
SDG 3: Good Health and Well-Being	0.83	0.99	0.99	0.90	0.92	0.49	0.93	0.00	0.96	0.85
SDG 5: Gender equality	1.00	0.53	0.53	0.40	0.40	0.44	0.44	0.00	0.53	0.43
SDG 6: Clean Water and Sanitation	0.60	0.67	1.00	0.83	0.91	0.92	0.97	0.36	0.95	0.89
SDG 7: Affordable and Clean Energy	0.69	0.75	1.00	0.81	0.56	0.19	0.64	0.26	0.54	0.67
SDG 8: Decent work and economic growth	0.47	0.54	0.88	0.47	0.43	0.34	0.47	0.23	0.53	0.44
SDG 9: Industry, innovation and infrastructure	0.59	0.68	0.83	0.76	0.69	0.12	0.47	0.45	0.56	0.75
SDG 10: Reduced inequalities	0.00	0.76	1.00	0.38	0.23	0.46	0.47	0.20	0.65	0.23
SDG 11: Sustainable Cities and Communities	0.71	1.00	1.00	0.95	0.97	0.29	0.80	0.55	0.74	0.88
SDG 12: Responsible Consumption and Production	0.39	1.00	1.00	0.78	0.81	0.44	0.63	0.88	0.72	0.87
SDG 13: Climate Action	0.93	1.00	1.00	0.99	0.99	0.05	0.54	0.00	1.00	0.89
SDG 14: Life Below Water	0.59	0.99	1.00	0.83	0.90	0.34	0.82	0.04	0.81	0.86
SDG 15: Life on Land	0.56	0.85	0.92	0.90	0.91	0.30	0.84	0.40	0.91	0.74
SDG 16: Peace, Justice and Strong Institutions	1.00	0.53	0.53	0.40	0.40	0.44	0.44	0.00	0.53	0.43

Table S10. Normalized matrix of SDGs with statistical analysis

SDGs	Solar PV	Reservoir	R-o-R	Wind - onshore	Wind - offshore	Oil	Gas	Coal	Nuclear	Biogas	Mean (μ)	Standard deviation (σ)	μ-σ	μ+σ
SDG 1: No poverty	0.36	0.38	1.00	0.26	0.27	0.26	0.25	0.21	0.34	0.32	0.36	0.22	0.15	0.58
SDG 2: Zero Hunger	0.48	0.94	1.00	0.96	0.97	0.27	0.96	0.53	0.98	0.81	0.79	0.25	0.54	1.04
SDG 3: Good Health and Well-Being	0.83	0.99	0.99	0.90	0.92	0.49	0.93	0.00	0.96	0.85	0.79	0.29	0.49	1.08
SDG 5: Gender equality	1.00	0.53	0.53	0.40	0.40	0.44	0.44	0.00	0.53	0.43	0.47	0.23	0.24	0.70
SDG 6: Clean Water and Sanitation	0.60	0.67	1.00	0.83	0.91	0.92	0.97	0.36	0.95	0.89	0.81	0.19	0.62	1.00
SDG 7: Affordable and Clean Energy	0.69	0.75	1.00	0.81	0.56	0.19	0.64	0.26	0.54	0.67	0.61	0.23	0.38	0.84
SDG 8: Decent work and economic growth	0.47	0.54	0.88	0.47	0.43	0.34	0.47	0.23	0.53	0.44	0.48	0.16	0.32	0.64
SDG 9: Industry, innovation and infrastructure	0.59	0.68	0.83	0.76	0.69	0.12	0.47	0.45	0.56	0.75	0.59	0.20	0.39	0.79
SDG 10: Reduced inequalities	0.00	0.76	1.00	0.38	0.23	0.46	0.47	0.20	0.65	0.23	0.44	0.28	0.15	0.72
SDG 11: Sustainable Cities and Communities	0.71	1.00	1.00	0.95	0.97	0.29	0.80	0.55	0.74	0.88	0.79	0.22	0.58	1.01
SDG 12: Responsible Consumption and Production	0.39	1.00	1.00	0.78	0.81	0.44	0.63	0.88	0.72	0.87	0.75	0.20	0.55	0.95
SDG 13: Climate Action	0.93	1.00	1.00	0.99	0.99	0.05	0.54	0.00	1.00	0.89	0.74	0.38	0.36	1.12
SDG 14: Life Below Water	0.59	0.99	1.00	0.83	0.90	0.34	0.82	0.04	0.81	0.86	0.72	0.29	0.42	1.01
SDG 15: Life on Land	0.56	0.85	0.92	0.90	0.91	0.30	0.84	0.40	0.91	0.74	0.73	0.22	0.51	0.95
SDG 16: Peace, Justice and Strong Institutions	1.00	0.53	0.53	0.40	0.40	0.44	0.44	0.00	0.53	0.43	0.47	0.23	0.24	0.70

Table S11. Power technology score considering the company's focused SDG

Sector	Company	Power Technology										Mean (μ)	Standard deviation (σ)	μ-σ	μ+σ
		Solar PV	Reservoir	R-o-R	Wind - onshore	Wind - offshore	Oil	Gas	Coal	Nuclear	Biogas				
Oil & Gas	Saudi Aramco	0.56	0.77	0.90	0.74	0.74	0.38	0.67	0.33	0.71	0.70	0.65	0.17	0.48	0.82
	ExxonMobil	0.55	0.91	1.00	0.81	0.74	0.32	0.63	0.58	0.68	0.80	0.70	0.19	0.51	0.89
	Total Energies	0.55	0.70	0.89	0.66	0.61	0.23	0.49	0.34	0.59	0.59	0.56	0.17	0.39	0.74
	Chevron	0.64	0.75	0.96	0.71	0.62	0.33	0.64	0.17	0.67	0.64	0.61	0.21	0.40	0.82
Technology	Microsoft	0.61	0.61	0.85	0.54	0.50	0.31	0.47	0.17	0.60	0.50	0.52	0.17	0.34	0.69
	Alphabet (Google)	0.57	0.82	0.96	0.77	0.73	0.29	0.66	0.43	0.73	0.71	0.67	0.18	0.48	0.85
	Amazon	0.58	0.82	0.95	0.77	0.75	0.41	0.71	0.35	0.75	0.74	0.68	0.18	0.51	0.86
	NVIDIA	0.71	0.82	0.90	0.83	0.80	0.25	0.64	0.25	0.75	0.80	0.67	0.22	0.45	0.90
Food & Beverages	Anheuser-Busch InBev	0.59	0.79	0.95	0.73	0.70	0.44	0.67	0.37	0.71	0.72	0.67	0.16	0.51	0.83
	Mondeléz International	0.53	0.83	0.97	0.76	0.78	0.46	0.73	0.43	0.79	0.76	0.71	0.16	0.54	0.87
	Danone	0.53	0.83	0.97	0.76	0.78	0.46	0.73	0.43	0.79	0.76	0.71	0.16	0.54	0.87
	Archer-Daniels-Midland Company (ADM)	0.56	0.71	0.93	0.74	0.74	0.43	0.72	0.30	0.79	0.68	0.66	0.17	0.49	0.83

Table S12. Multi-Criteria Decision Analysis

Company	Weighting	Power Technology										Mean (μ)	Standard deviation (σ)	μ-σ	μ+σ
		Solar PV	Reservoir	R-o-R	Wind - onshore	Wind - offshore	Oil	Gas	Coal	Nuclear	Biogas				
Saudi Aramco	Equal	0.554	0.634	0.897	0.666	0.518	0.296	0.659	0.255	0.524	0.593	0.560	0.175	0.385	0.735
	S	0.531	0.546	0.788	0.560	0.510	0.308	0.516	0.214	0.486	0.469	0.493	0.145	0.348	0.638
	T	0.555	0.557	0.956	0.665	0.316	0.200	0.739	0.215	0.372	0.578	0.515	0.229	0.286	0.744
	E	0.576	0.798	0.946	0.773	0.729	0.380	0.723	0.337	0.713	0.731	0.671	0.178	0.492	0.849
ExxonMobil	Equal	0.551	0.748	0.999	0.752	0.514	0.243	0.695	0.423	0.517	0.710	0.615	0.200	0.416	0.815
	S	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	T	0.554	0.583	1.000	0.693	0.281	0.166	0.764	0.264	0.345	0.615	0.526	0.247	0.279	0.774
	E	0.547	0.914	0.998	0.810	0.748	0.320	0.626	0.582	0.689	0.806	0.704	0.186	0.518	0.890
Total Energies	Equal	0.547	0.656	0.911	0.658	0.509	0.209	0.562	0.306	0.514	0.588	0.546	0.183	0.363	0.729
	S	0.482	0.551	0.812	0.564	0.516	0.260	0.471	0.253	0.476	0.461	0.485	0.150	0.335	0.634
	T	0.552	0.567	0.962	0.661	0.312	0.163	0.697	0.236	0.368	0.576	0.509	0.229	0.280	0.739
	E	0.608	0.850	0.960	0.749	0.699	0.204	0.518	0.428	0.699	0.726	0.644	0.206	0.438	0.850
Chevron	Equal	0.615	0.681	0.961	0.686	0.507	0.284	0.664	0.176	0.570	0.614	0.576	0.208	0.368	0.783
	S	0.532	0.603	0.917	0.565	0.460	0.318	0.553	0.208	0.549	0.512	0.522	0.176	0.345	0.698
	T	0.581	0.577	0.983	0.673	0.311	0.195	0.741	0.181	0.392	0.587	0.522	0.241	0.281	0.763
	E	0.732	0.862	0.983	0.819	0.749	0.339	0.697	0.140	0.768	0.742	0.683	0.239	0.444	0.922
Microsoft	Equal	0.744	0.770	0.913	0.725	0.706	0.202	0.502	0.097	0.765	0.660	0.608	0.250	0.358	0.859
	S	0.620	0.618	0.854	0.550	0.516	0.306	0.477	0.161	0.610	0.510	0.522	0.178	0.344	0.700
	T	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	E	0.868	0.922	0.971	0.899	0.895	0.098	0.528	0.032	0.920	0.810	0.694	0.336	0.359	1.030
Alphabet (Google)	Equal	0.541	0.665	0.953	0.672	0.494	0.257	0.658	0.311	0.546	0.608	0.570	0.186	0.384	0.757
	S	0.500	0.596	0.914	0.559	0.455	0.306	0.550	0.266	0.539	0.510	0.520	0.167	0.353	0.686
	T	0.549	0.571	0.980	0.667	0.305	0.183	0.739	0.239	0.382	0.584	0.520	0.234	0.286	0.754
	E	0.574	0.828	0.966	0.788	0.722	0.281	0.686	0.429	0.717	0.729	0.672	0.188	0.484	0.860
Amazon	Equal	0.569	0.654	0.936	0.660	0.491	0.310	0.678	0.259	0.549	0.613	0.572	0.183	0.389	0.754
	S	0.562	0.590	0.873	0.548	0.451	0.338	0.556	0.221	0.539	0.511	0.519	0.161	0.357	0.680

	T	0.561	0.566	0.973	0.662	0.304	0.206	0.747	0.216	0.383	0.587	0.520	0.233	0.288	0.753
	E	0.583	0.806	0.962	0.771	0.717	0.386	0.731	0.339	0.723	0.740	0.676	0.180	0.495	0.856
NVIDIA	Equal	0.773	0.509	0.824	0.872	0.616	0.155	0.705	0.129	0.469	0.760	0.581	0.252	0.330	0.833
	S	0.689	0.521	0.624	0.826	0.835	0.159	0.576	0.091	0.490	0.564	0.538	0.235	0.303	0.772
	T	0.903	0.218	0.925	0.945	0.264	0.066	0.873	0.055	0.201	0.897	0.535	0.379	0.156	0.914
	E	0.726	0.788	0.923	0.845	0.748	0.239	0.665	0.241	0.715	0.820	0.671	0.226	0.445	0.897
Anheuser-Busch InBev	Equal	0.572	0.658	0.941	0.657	0.488	0.333	0.667	0.282	0.545	0.621	0.576	0.176	0.400	0.753
	S	0.564	0.592	0.875	0.546	0.450	0.348	0.551	0.232	0.538	0.515	0.521	0.159	0.362	0.680
	T	0.562	0.568	0.975	0.661	0.303	0.216	0.742	0.226	0.381	0.590	0.522	0.230	0.292	0.753
	E	0.590	0.814	0.974	0.764	0.711	0.436	0.707	0.390	0.716	0.759	0.686	0.165	0.521	0.851
Mondeléz International	Equal	0.510	0.735	0.942	0.664	0.655	0.421	0.640	0.365	0.702	0.649	0.628	0.156	0.472	0.784
	S	0.483	0.608	0.903	0.538	0.502	0.369	0.526	0.276	0.590	0.507	0.530	0.156	0.374	0.686
	T	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	E	0.538	0.862	0.980	0.789	0.809	0.474	0.754	0.454	0.815	0.792	0.726	0.167	0.559	0.894
Danone	Equal	0.510	0.735	0.942	0.664	0.655	0.421	0.640	0.365	0.702	0.649	0.628	0.156	0.472	0.784
	S	0.483	0.608	0.903	0.538	0.502	0.369	0.526	0.276	0.590	0.507	0.530	0.156	0.374	0.686
	T	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	E	0.538	0.862	0.980	0.789	0.809	0.474	0.754	0.454	0.815	0.792	0.726	0.167	0.559	0.894
Archer-Daniels-Midland Company (ADM)	Equal	0.543	0.674	0.921	0.680	0.671	0.409	0.662	0.288	0.734	0.622	0.620	0.166	0.454	0.786
	S	0.493	0.588	0.897	0.543	0.507	0.365	0.534	0.251	0.600	0.498	0.528	0.158	0.369	0.686
	T	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	E	0.592	0.760	0.945	0.817	0.834	0.453	0.790	0.326	0.867	0.746	0.713	0.186	0.527	0.899

*S – Social overweighted. T – Technological overweighted. E – Environmental overweighted.

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