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INTEGRATION OF LIFE CYCLE SUSTAINABILITY ASSESSMENT INDICATORS IN DIFFERENT ENERGY SECTORS

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ABSTRACT: Despite the increasing number of studies analysing sustainability performance in energy-related field, most of the existing papers present the results of particular dimensions separately. A number of methods have been identified to integrate individual LCSA indicators and determine one final sustainability score which could be a relevant support for decision-makers to rank scenarios being compared at the interpretation phase. In the current stage, none of the proposed methods seem to be in a leading position. The integration of sustainability indicators still suffers from the lack of harmonisation concerning the selection and definition of impact categories to be analysed, as well as specific procedures that would allow the results to be reliably compared. The procedures often assume arbitrarily determined weights of importance for aggregating environmental, economic and social scores, which can raise controversy. The development of noncontroversial methods to integrate LCSA indicators is also recommended from the perspective of future standardisation.

KEYWORDS: power generation, energy use, sustainability, LCA, LCC, S-LCA, LCSA

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Introduction

The assessment of energy production considering economic, environmental and social aspects has received growing attention in recent years. There are a number of reasons for this, including increasing energy prices caused by disrupted supply chains of energy carriers as well as higher requirements for environmental performance of energy generation due to the goals of sustainable development (United Nations, 2015) and the transition of Europe towards climate neutrality by 2050 (Communication, 2018, 2019). To analyse the environmental, economic and social impact, the life cycle perspective is recommended as the most relevant effects may occur in upstream or downstream processes of energy generation. The methods applied for the three pillars of sustainability are life cycle assessment (LCA), life cycle costing (LCC) and social life cycle assessment (S-LCA). The combined application of the three tools is known as the life cycle sustainability assessment (LCSA). The individual tools used for environmental, economic and social impact assessment are continuously developed. However, the integration of LCA, LCC and S-LCA still suffers from the lack of harmonisation of the specific procedures involved as well as reliable results comparison (Costa et al., 2019; Tan et al., 2023). Selecting the most sustainable energy option decision-makers needs a coherent approach comprising the complexity of all the dimensions considered (Balasbaneh et al., 2024). The need to develop this field resulted in a growing number of publications related to LCSA in recent years (Fauzi et al., 2019), demonstrating increasing interest in sustainability assessment related to energy (Hayatina et al., 2023; Visentin et al., 2020). The studies concerning this field, including electricity, bioenergy and fuels, account for a significant proportion of 36% of all LCSA papers recently considered by Padilla-Rivera et al. (2023).

Comparing various energy generation technologies and considering their interaction with different systems (economy, nature, society) poses a challenge. It is difficult to compare numerical results expressing incomparable phenomena, especially when indicators obtained with different methods lead to opposite conclusions. Presentation of complex LCSA indicators in a disaggregated way can represent a barrier to understanding the results by decision-makers and raise the risk of drawing incorrect conclusions (Traverso et al., 2012a). To address the difficulty, specific methods have been developed to solve interdisciplinary issues. For instance, specially created procedures for determining the weighting coefficients (Grubert, 2017) or multi-criteria decision analyses, including multi-attribute value theory (Ekener et al., 2018), the analytic hierarchy process (AHP) (Ren et al., 2017), or life cycle sustainability dashboard (LCSD) method (Traverso et al., 2012b) could be applied in this case. The solutions developed allow the mitigation of the problem with results communication and provide a better understanding of LCSA by non-expert stakeholders.

The problem concerning integrating incomparable results occurs also on the lower level of LCSA. For instance, in the case of life cycle assessment, the indicators represent plenty of different impact categories which are difficult to refer to each other. However, some solutions have been developed to make it easier to interpret the results and draw definitive conclusions (single score procedure based on weighting (International Organization for Standardization, 2006b) or mixing triangle method (Hofstetter et al., 1999)).

Highlighting the issue of compiling results concerning different fields, the main objective of this study is to identify the methods used to integrate various indicators of life cycle sustainability assessment in the energy supply sector. The literature review aims to find potential gaps in integrating the LCSA indicators as well as provide a recommendation for convenient solutions for the presentation of the complex sustainability results to decision-makers in a comprehensive and understandable way. The necessity to enhance the interpretation stage of sustainability assessment is most relevant not to LCSA experts but primarily to stockholders who need to be supported in decision processes concerning, for instance, developing generating technologies in the power industry, green energy procurement by public administrations or selection of heating solutions or insulation materials by consumers.

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The methods comprising life cycle sustainability assessment

Life cycle assessment

To represent all the sustainability pillars, LCSA consists of the three methods dedicated to determining the environmental, economic and social impact. All the methods consider the life cycle perspective, which means that not only the direct impact exerted by the main production process is taken into account, but also all the upstream and downstream processes with their effects. This pattern was adopted from the life cycle assessment method, where the extraction of resources is the starting process, followed by transport, processing, production, distribution, use, and disposal, according to the grave approach. A wide perspective allows us to identify and avoid potential pollution transfer between particular life cycle stages (Larsen et al., 2022).

Life cycle assessment is the most mature among other elements of LCSA. The requirements and guidelines, as well as the principles and framework of LCA, are provided by international standards (International Organization for Standardization, 2006a, 2006b). The LCA framework consists of four phases, namely: goal and scope definition, life cycle inventory (LCI), life cycle impact assessment (LCIA), and interpretation. The initial phase consists of the definition of the basic assumptions of a study, such as the objective, system boundaries, and functional unit. The life cycle inventory requires detailed industrial data concerning the manufacturing of the product to be investigated and its environmental impact. Specialised databases are often used, especially for upstream or downstream processes. The last step of the inventory analysis is developing an inventory table that includes all environmental impacts and a breakdown of individual processes. The table is also the dataset for the following phase of the life cycle impact assessment. The impact assessment may be carried out using various methods (e.g., CML, ReCiPe 2016, TRACI, Cumulative Energy Demand). Common elements of the methods are procedures processing the numerical industrial data into environmental impact indicators. Classification is a mandatory procedure which aims to assign inventory data to environmental impact categories. The subsequent procedure is a characterisation that may be carried out for midpoint or endpoint levels. The midpoint mode is the last mandatory element of LCIA. The idea of this stage is to determine impact indicators for all selected impact categories based on inventory data and corresponding characterisation factors. The results represent the amount of environmental load and are expressed in mass, volume or area units, e.g. the climate change is expressed in the equivalent of 1 kilogram of carbon dioxide emission (1 kg of CO2-eq). The number of impact categories is often greater than 10 (for instance, the ReCiPe 2016 method considers 17 categories), which may raise some problems with the unambiguous interpretation of the outcomes of the analysis. Characterisation at the endpoint level is conducted for a few (usually three or four) damage categories that result from the aggregation of environmental effects by applying mid-to-endpoint factors specific to individual impact categories. The procedure leads to obtaining endpoint indicators which reflect the damage to the environment in the analysed scopes. Positioning different products based on three numerical results is usually easier than interpreting 17 indicators. However, particular endpoint outcomes may also lead to opposite conclusions, making it challenging to provide a clear recommendation (Huijbregts et al., 2017).

Life cycle costing

The product life cycle approach (represented in the LCA technique) can be used to assess economic aspects (Joachimiak-Lechman, 2014). The life cycle costing (LCC) method evolved based on earlier experiences and achievements gained in the formulation of LCA, the most developed of all life cycle sustainability assessment methods. However, LCC, when used as a separate tool for financial calculations through the life cycle, is even older than life cycle assessment (Settanni et al., 2011). The environmental context was not included in the original development of life cycle costing. 'Traditional' LCC is an investment calculation method used to classify various investment options (Gluch & Baumann, 2004). A fundamental reason for conducting LCC analysis is a complete calculation of financial costs of life cycle environmental aspects and impacts eventually resulting from a decision (Swarr et al., 2011). Thuss, according to the definition, the aim of LCC is to determine all financial costs related to the product life cycle that are directly incurred by this cycle participant, such as producers, suppliers or users. The term "directly" means their own (or internal) costs that must be borne by an entity

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(Joachimiak-Lechman, 2014). Despite the similarity of the LCA and LCC names, significant methodological differences can be noticed between both techniques (Norris, 2001). In the LCC method, the following stages are established: defining the goal and scope, economic life-cycle inventory, interpretation and data reviewing (Joachimiak-Lechman, 2014). Differences also occur in the use phase – the economic lifetime may be shorter than presented in the LCA, which results from an entity accounting practice. LCC analysis involves only those processes that are associated with direct economic costs (or benefits). It is worth noting that some cost flows may not reflect or even present any relationships with physical flows in the LCA study (Norris, 2001). To simplify the analysis, environmental life cycle costing, which translates environmental problems into monetary units, is presented in one-dimensional units (e.g., dollars, euros, etc.) (Gluch & Baumann, 2004; Norris, 2001). LCC analysis is usually based on strictly economic indicators such as Net Present Value (NPV) or the Levelized Cost of Energy (LCOE) (Gavaldà et al., 2022). The LCOE estimates the cost of generating 1 kWh of electricity by relating the generation cost to the amount of energy produced. It represents the ratio of the NPV of all expenses over the life of a power plant considered (including costs of designing, construction, financing, operation, maintenance, and disposal) to the total electricity generated by the plant (Baindu Gobio-Thomas et al., 2023; Yuan et al., 2021). It is a key indicator for long-term energy planning and cost-based decisions (Gavaldà et al., 2022). The correlation between LCOE and LCA results was demonstrated by (Gasa et al., 2022; Tan et al., 2023).

To date, life cycle costing has not been standardised by any of the international ISO standards. However, a code of practice has been published to provide a framework for performing the financial impact of products (Swarr et al., 2011).

Social life cycle assessment

Social life cycle assessment (S-LCA) is a method applied to express social and socio-economic dimensions of products, services and projects, taking into account positive and negative (as well as actual and potential) impacts throughout the life cycle. Nowadays, no standardised methods for conducting S-LCA exist (Larsen et al., 2022). However, the guideline published by the UNEP/SETAC Life Cycle Initiative may become the solution of this issue (Benoît & Mazijn, 2009). The stages of S-LCA analysis are often, but not always, the same as those used for life cycle assessment (Larsen et al., 2022). Impacts are related to the effects experienced by the concerned stakeholders and expressed by social indicators (Lucchetti et al., 2018). The stakeholders include employees, the local community and social groups defined by various features like freedom of association, accidents at work, living wages, generation of wastes, workplace creation, use of local labour, use of business-creating innovations, proximity to local supply facility, local community complaints contributing, developing of innovations, technology exchange as well as involvement in financial development (Balasbaneh & Marsono, 2020). The diversity of indicators in the S-LCA results from differences related to sustainable behaviour, human rights, health, number of fatalities, safety, cultural heritage, socio-economic issues, and labour policies. Presently, no agreement has been reached on the selection of impact categories and the development of harmonised methods to use for S-LCA analysis (Larsen et al., 2022). Some methods use midpoint indicators, while others use endpoint indicators. The difference is due to the position of the indicators on the impact pathway model (Jørgensen et al., 2008). What distinguishes S-LCA from LCA and LCC is the fact that S-LCA involves stakeholders in defining the goal and scope, collecting data and interpreting it (Larsen et al., 2022). Performing S-LCA analysis enables the improvement of the socio-economic conditions of stakeholders, both directly or indirectly, related to the product life cycle (Lucchetti et al., 2018).

Unlike LCA, social life cycle assessment has not been standardised by any international standard to date. However, United Nations Environmental Programme has developed a guideline for practitioners carrying out the assessment of the social impacts of product life cycle (Benoît & Mazijn, 2009).

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Integration of individual dimensions of LCSA results

Life cycle assessment and life cycle costing are similar methods, but combining them generates barriers and difficulties due to the differences between environmental and economic aspects. One of the issues is to determine the product system boundaries for LCA and LCC, aiming to avoid double costing. Moreover, in case of presentation and interpretation of the LCA, the damage indicators are assigned to the categories such as: human health, ecosystem quality, climate change and resources, whereas, results of LCC can be divided into the following groups: fixed and variable costs, direct and indirect costs, recurring and non-recurring costs, or according to life cycle participants (Joachimiak-Lechman, 2014).

An attempt to solve the problem of discrepancy between LCA and LCC was the Material Flow Cost Accounting. The method was based on a flow-oriented accounting approach that considers material and energy flows occurring in manufacturing processes – both products and undesired flows representing inefficiencies and losses. The flows were expressed in terms of monetary values (Bierer et al., 2015).

A software tool aimed at integrating LCA and LCC results to support the decision-making process at the design phase of thermal renovation carried out in the building sector was presented by Baldoni et al. (2021). The operation of the tool was demonstrated with a specific case study comparing five thermal insulation materials applied in a building for its energy efficiency improvement. To express the environmental impact, three midpoint categories were selected: global warming, acidification, and eutrophication sourced from the CML-2001 LCIA method. The selection was justified by the reference recommending the most significant categories for comparing the insulation systems (Bueno et al., 2016). The LCC output was represented by global cost (expressed in EUR) and payback period as a supportive indicator (years). The results of individual categories showed certain discrepancies. From economic and eutrophication points of view, the best option was the application of expanded polystyrene, whereas from the perspective of global warming and acidification, rock wool. However, the software did not provide any definite interpretation of the indicators. The authors stated that the tool developed by them is supposed only to guide users to the optimal decision, and the trade-off between particular categories should be resolved by assigning a specific weighting scheme dependent on the personal needs of the users (Baldoni et al., 2021).

The studies on sustainability assessment in the building and construction sector were analysed by Dong et al. (2023) to examine the compliance of used methods with the ten principles of LCSA application proposed by Life Cycle Initiative (Valdivia et al., 2021). The paper showed a very large discrepancy between the methods applied by individual studies conducted in this field. The principle that indicated the highest alignment was 'transparency' with an average score of 78%, whereas the lowest result, 9%, was obtained by 'product utility beyond functional unit'. However, the other analysis considering a wider scope of sectors concluded that 'transparency' was not properly addressed in most LCSA studies (Leroy-Parmentier et al., 2023).

Martinez-Hernandez et al. (2022) analysed biomass combined heat and power systems (CHP) located at a sawmill in the context of life cycle sustainability assessment. Two scenarios were studied: the present scenario with limited generation and the generation expansion scenario. The first scenario covered heat and electricity production for one's own needs, with the total electric power of the installation not exceeding 500 kW. In the second scenario, the CHP capacity was increased by 1 MW, assuming that the surplus of energy produced would be delivered to local habitats. For LCSA, the authors analysed a total of 29 indicators. Four indicators were analysed in the context of process aspects. As a part of the study concerning economic aspects, five indicators were analysed: internal rate of return, capital costs, operating costs, feedstock costs and cost of production. Eight indicators were used to analyse environmental impact: global warming, fossil fuels, photochemical ozone formation, acidification, eutrophication, ecotoxicity, and water consumption. Indicators regarding social aspects were divided into global and local. Global aspects included labour rights and decent work, health and safety, human rights, governance and community infrastructure, while local aspects involved total forest area, direct permanent jobs, gender equality, energy access, water access and sanitation access. The results were presented in a table as benefits, avoidances or savings of expansion scenarios compared to the baseline model for each group of indicators separately. For all the sustainability dimensions, the possibilities to significantly improve the analysed impact were demon-

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strated. In the CHP expansion scenario, the cost of electricity generation was 0.023 USD per kWh, while the electricity grid average rate at that time was 0.085 USD per kWh. Life cycle assessment indicated environmental impact decreased by 20%-95% depending on individual indicators. In the case of social indicators, benefits were observed, such as the potential creation of new places of work and the local habitant's complete satisfaction with the electricity supply (Martinez-Hernandez et al., 2022).

The life cycle sustainability assessment of a light rail transit system in Kayseri, Turkey, was analysed as a groundbreaking study integrating LCA, LCC, and S-LCA in the transportation field. Sustainability effects were referred to 1 passenger-km as a functional unit. The environmental impact was analysed by adopting the CML-IA baseline method, including nine impact categories (abiotic depletion potential, global warming potential, ozone layer depletion potential, human toxicity potential, freshwater aquatic ecotoxicity, terrestrial ecotoxicity, photochemical oxidation, acidification, eutrophication). LCC categories were costs of material, transportation, energy, and disposal, representing internal costs, as well as environmental and total costs, representing external costs. The resulting indicators were expressed in USD. Social impact was considered for four stakeholders (listed in bullets) with respective subcategories (in brackets):

- Worker (health and safety, fair salary, working hours, child labour),
- Consumer (health and safety, feedback mechanism, transparency),
- Local community (local employment, access to immaterial resources),
- Society (technology and development, public commitment to sustainability issues).

The LCA indicators for individual categories were presented with a breakdown by particular life cycle stages of the studied transportation system to allow the identification of the most relevant sources of problems. In the case of LCC and S-LCA, the results were presented for categories considered without additional breakdown. Also, the authors' recommendations were formulated separately for each sustainability aspect. However, there were some common conclusions resulting from different LCSA methods: 'reduction of electricity consumption' (environmental recommendation) was in line with 'reduction in energy costs' (economic recommendation). An application of a multi-criteria decision-making approach was suggested for future research in this field (Gulcimen et al., 2021).

Within the scientific community, there is still a lack of a universally accepted standard for aggregation of environmental, social, and economic indicators. Various models and approaches, including operations research, multi-attribute decision-making methods, multi-objective decision-making methods, data envelopment analysis, and other methods, are proposed to express the complexity of sustainability. The evaluation of individual methods is possible by applying them to the same case studies (Crippa & Ugaya, 2023; Thies et al., 2019).

An example of applying a type of multi-criteria decision analysis was a comparison of life cycle sustainability assessment results of conventional and underground pumped hydro energy storage presented by Guo et al. (2019). To express environmental impact, the authors used categories of global warming, acidification, eutrophication, photochemical ozone creation, human toxicity, blue water footprint and ecological footprint. Economic assessment was provided by indicators of capital cost, cost of operation and maintenance, levelized cost of electricity, levelized cost of storage and payback time. Social effects were reflected by employment, availability factor, contribution to peak (flexibility of electricity generation), dependence on fossil energy and the available capacity of the analysed technologies. In addition to a separate discussion of the results within each category, a multi-attribute value theory was applied to comprehensively compare the sustainability of studied technologies. The method adopted Equation 1.

$$v(a) = \sum_{i=1}^{I} w_i v_i(a), \quad (1)$$

where:
v(a) – overall sustainability score of considered solution,
w_i – the weight of importance for dimension i,
v_i (a) – score reflecting the performance in category i,
I – total number of decision criteria.

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In order to standardise the numerical input data, the authors assumed the score of the better solution within the individual category to be 1, and the score of the worse solution results from the proportion between both solutions. This approach allowed us to obtain a definite interpretation of the indicators; conventional pumped hydro energy storage turned out to have significantly better overall sustainability performance than underground solution, despite the latter indicating higher social performance. Modification of particular weights (w_i) showed that the overall sustainability score would be better for underground energy storage if the weighting coefficients for the social dimension were three times greater than those for economic and environmental (0.6: 0.2: 0.2) (Guo et al., 2019).

The application of a life cycle sustainability dashboard in the LCSA of photovoltaic (PV) modules was demonstrated by Traverso et al. (2012a). The aim of the case study was to compare the sustainability performance of three PV module scenarios with a boundary system limited to the assembly stage. LCA part adopted the Eco-indicators 99 LCIA method with eleven impact categories: carcinogens, respiratory organics and inorganics, climate change, radiation, ozone layer, acidification/eutrophication, ecotoxicity, land use, minerals and fossil fuels. To express economic impact, total assembly cost was taken into account, including individual costs of PV cells, other materials, equipment, electricity and labour force. Social effects were determined by considering discrimination, child labour, wages, working hours, social benefits and health conditions. The integration of the results was provided by assigning the same numerical weight or importance to all the indicators determined within particular sustainability pillars. Consequently, three single scores were obtained for LCA, LCC and S-LCA separately. The further aggregation of the results was carried out by giving the same 1/3 weighting coefficients to each of the three scores and adding them together. The procedures were performed with Excel, which enabled the creation of pie charts (dashboards) illustrating the numerical results by intuitive colour representation. Thanks to this solution, not only the final ranking scores (positioning the analysed scenarios) but also the individual indicators were clearly visible. An optional feature of LCSD designed in this way was the possibility of modifying the weights of each category separately (Traverso et al., 2012b).

Keller et al. (2015) formulated a method of integrated life cycle sustainability assessment (ILCSA) based on the existing life cycle sustainability assessment (LCSA) framework but extended to ex-ante assessment. The new method introduced a structured discussion of results leading to specific conclusions and recommendations, making it valuable for decision-makers. Moreover, it extended LCA and LCSA of impact issues that can be considered in practice and better assess uncertainties associated with potential future systems. The developed method was practically applied in a few projects, including the evaluation of the lignocellulosic biorefinery concept. In this case, the authors used various LCA, LCC, and S-LCA indicators. The environmental impact was considered using some categories taken from the ReCiPe method, e.g. climate change, terrestrial acidification, and marine eutrophication. the economic field, net present value, total capital investment and CO2 avoidance costs were analysed, among others. The social effects were expressed by the production of feedstock, identification of stakeholders, rural development, labour conditions and competition with other sectors. The environmental, economic and social issues are assessed based on the same settings and definitions. In addition to LCA, LCC and S-LCA research, integrated life cycle sustainability assessment enables the incorporation of typical assessment methods, considering both qualitative and quantitative indicators. The integration of the results includes the procedure comprising the subsequent steps. First, scenarios and categories that are important to the decision options should be selected. The categories set may be completed with relevant interdisciplinary ones. Then, all the scenarios and indicators are presented in overview tables that should contain qualitative and quantitative data. In order to increase readability, qualitative and quantitative data should be categorised and marked in the same colours. The results integration is based on the benchmarking procedure that allows a comparison of all scenarios to the baseline scenario. Quantitative differences between scenarios and the baseline scenario are categorised as advantageous [+], neutral [0] or disadvantageous [-]. If the analysed scenario obtains better results under less favourable conditions than the baseline scenario under standard conditions, it receives a very advantageous score [++]. Results that are, e.g. 10% better than the baseline scenario in all direct comparisons under identical conditions are rated as advantageous [+]. For the ratings disadvantageous [-] and very disadvantageous [--], the assessment is performed analogously. Qualitative indicators are assessed according to the same procedure, excluding the use of

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minimal differences. The benchmarking procedure is followed by a structured discussion leading to recommendations concerning analysed technologies (Keller et al., 2015).

To integrate assessment results of the sustainability performance of various electricity generation technologies, data envelopment analysis (DEA) has also been developed. To avoid standard DEA's drawbacks associated with the subjectivity of weights definition and the necessity to reveal the preferences of decision-makers, the method was combined with the order of efficiency concept. The six-step algorithm was proposed to assess the sustainability performance. The first step included categorising individual criteria into three particular dimensions (pillars of sustainability). The environmental impact was represented by nine midpoint categories: global warming, ozone depletion, acidification, eutrophication, photochemical smog, freshwater eco-toxicity, marine eco-toxicity, land occupation and land eco-toxicity. The economic effects were expressed by capital cost, operation and maintenance cost as well as fuel cost. The social impact was reflected by direct employment, worker injuries, human toxicity potential, total radiation, depletion of elements and depletion of fossil fuels. In the second step, all possible combinations of input data were identified separately for each dimension. The third step processed numerical data to provide efficiency scores of all power technologies studied for each combination of input data. Before calculations, all the indicators were normalised to a common interval from 0 to 1. In the next step, the scores of subsequent orders as average efficiency scores for possible combinations were determined for all the technologies. In the fifth step, the overall efficiencies for the economic, environmental and social dimensions were obtained as the average scores of all orders considered. In the final step, based on efficiency scores for all dimensions, the overall sustainability performance indicator was calculated, allowing the ranking of all electricity generation technologies to be analysed. The calculations were performed by linear programming procedure with repeated iterations. Among the advantages of the presented method, the authors include the ability to manage a large number of economic, environmental and social categories, separate consideration of each pillar of sustainability, and the ability to rank individual technologies according to the degree to which they comply with sustainability principles, no need to assume preference weights for the categories, providing clear quantitative recommendations for solutions with low sustainable rank to increase their performance, possibility of application standard software packages for data processing (Galán-Martín et al., 2016).

A comprehensive energy-led sustainable assessment method, combining DEA with Slack-Based Measure model (SBM) as well as LCA, LCC and S-LCA, has been proposed to assess the energy efficiency of various production systems. In the baseline scenario, energy intensity per production unit and total global warming were implemented as environmental indicators, total energy cost per production unit and net benefit as economic indicators, and job years per consumed energy as a social indicator. For the improvement scenario, the social indicator was replaced with one, taking into account saved job-years. In order to compare the results, an energy-led sustainability performance index (I_{ESUS}) was calculated. I_{ESUS} was associated with indicators for each life cycle method, respectively environmental – I_{ENV}, economic – I_{ECO} and social – I_{SOC}. Quantitative comparison of aggregated indicators requires some calculations. Each life cycle method was represented by a set of indicators with different units. The indicators for each method were normalised to obtain relative values. The indicator for the environmental dimension (I_{EENV}) was calculated by Equation 2.

$$I_{EENV} = \sqrt{(I_{EENV1}^2 + I_{EENV1}^2 + I_{EENVn}^2)},\ for\ n = 10, \quad (2)$$

A normalised result was calculated for each method, taking the average of three minimum and three maximum values, according to Equation 3.

$$I_{EENV} = \frac{\text{Indicator (value achieved for each dimension)} - \text{min\_indicator}}{(\text{max\_indicator} - \text{min\_indicator})}. \quad (3)$$

Normalisation indicators for economic and social dimensions were determined in the same way. Finally, production systems were compared by separate environmental, economic and social aggregated results using the Energy Sustainability Index (I_{ESUS}). The indicator value was in the range of 1-3, where 0-1 meant energy unsustainable, the range 1-2 transitioned to energy sustainability, and the range 2-3 energy sustainability (Kluczek, 2019).

One of the approaches to sustainability assessment associated with energy efficiency is the Sustainable Energy Action Plan (SEAP) (Jekabsone et al., 2021). This is an operational tool used by European municipalities that participated in the Covenant of Mayors (CoM) initiative (Covenant of Mayors, 2018) to develop local actions aimed at meeting the target of at least 20% reduction of greenhouse gas emissions by 2020 compared to 1990 levels set by the EU "Climate–Energy Package" (Directive, 2009). The mandatory indicators of the tool were the reduction of CO2 emissions, energy use, generation from renewable energy sources (RES) and savings indicators for each action. SEAP also included a range of optional indicators such as energy delivered by electric vehicle charging stations, public lighting systems electrical consumption, litres of water delivered by public water houses, photovoltaic systems electricity production, amount of ligneous biomass consumed and thermal power delivered to district heating final users (Fresner et al., 2019). In 2015, the framework of SEAP was replaced with the Sustainable Energy and Climate Action Plan (SECAP) to take into account the amended targets of at least 55% greenhouse gas emission reduction by 2030 and eventually achieving climate neutrality by 2050, according to the EU commitments (Colocci et al., 2023; Di Battista et al., 2021). The scope of issues considered by SACAP was extended compared to SEAP. The set of indicators was expanded to include the length of transport network located in areas at risk (e.g. flood/drought/forest fire), number of consecutive days without rainfall, % of habitat losses from extreme weather events, % of livestock losses from pests, % of transport, energy, water, waste, ICT infrastructure retrofitted for adaptive resilience, % of coastline designated for managed realignment, % of forest restored (Fresner et al., 2019). The tool supporting local authorities in selecting the most efficient SECAP actions was proposed by (D'Orso et al., 2020). The method was based on a combination of modified AHP and geographic information systems. Reduction in energy consumption, reduction in GHG emission, costs and quality of life were considered as the criteria. The second-level weights were the ratios of a number of indicators expressing individual criteria and a total number of indicators, whereas the third-level weights were assigned by the stakeholders through a debate (D'Orso et al., 2023). The financial optimisation of SECAP actions was also analysed by Matak et al. (2022). To achieve more effective and advantageous effects of SECAP's actions, joint initiatives carried out jointly by a few municipalities in the same area were recommended to be considered (D'Onofrio et al., 2023).

The literature review of studies concerning sustainability assessment of energy systems reveals a variety of approaches to present the results in a form convenient for decision-makers by reducing the number of output indicators. Table 1 depicts the summary of solutions applied to combine environmental, economic and social scores. Most of the studies took into account all three sustainability dimensions. However, the cases dealing with SECAP used a specific approach not related to LCSA. The typical layout of the papers included the assessment method development and/or case study. The topics represented a wide range of various energy issues, including energy efficiency and storage, renewable sources as well as energy use in building and transport sectors. The number of sustainability categories ranged from 6-29, with the exceptions for analyses that excluded social aspects. In most studies, the results representing individual dimensions were presented separately. In the remaining studies, the integration procedures usually involve arithmetic means or arbitrarily determined weighting coefficients. Since the arbitrary components may seem controversial, particularly notable are the analyses that avoided the discretionary stages, which were made possible by the application of the benchmarking procedure (Keller et al., 2015), a graphical approach based on a 3-D chart (Kluczek, 2019) or the same monetary unit for all categories considered (Yuan et al., 2021).

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Table 1. Summary of integration approaches for sustainability dimensions

Reference	Considered dimensions	Study content	Energy sector	Number of categories	Integration to one score
Traverso et al. (2012a)	LCA+LCC+S-LCA	method development + case study	renewables	18	dashboard (arithmetic mean)
Traverso et al. (2012b)	LCA+LCC+S-LCA	method development	N/A	18	dashboard (arithmetic mean)
Keller et al. (2015)	LCA+LCC+S-LCA	method development + case study	biorefineries	26	benchmarking procedure
Bierer et al. (2015)	LCA+LCC	method development	N/A	N/A	N/A
Galán-Martín et al. (2016)	LCA+LCC+S-LCA	method development + case study	electricity generation	18	DEA (average of all computed scores)
Guo et al. (2019)	LCA+LCC+S-LCA	method development + case study	energy storage	17	multi-attribute value theory
Kluczek (2019)	LCA+LCC+S-LCA	method development + case study	energy efficiency	6	3-D chart
Fresner et al. (2019)	not LCSA related	case studies	SECAP	not LCSA related	N/A
Baldoni et al. (2021)	LCA+LCC	method development + case study	building	7	-
Gulcimen et al. (2021)	LCA+LCC+S-LCA	case study	transport	26	-
Jekabsone et al. (2021)	not LCSA related	case studies	SECAP	not LCSA related	N/A
Di Battista et al. (2021)	not LCSA related	case studies	SECAP	not LCSA related	N/A
Valdivia et al. (2021)	LCA+LCC+S-LCA	establishing principles	N/A	10 principles for LCSA	N/A
Yuan et al. (2021)	LCC based on ReCiPe	method development + case study	coal-fired, biomass, and wind power	2	sum of costs
Martinez-Hernandez et al. (2022)	LCA+LCC+S-LCA	case study	renewables	29	-
Matak et al. (2022)	not LCSA related	method development + case study	SECAP	not LCSA related	N/A
Gasa et al. (2022)	LCA+LCC	case study	concentrating solar power	4	N/A
Colocci et al. (2023)	not LCSA related	case studies for regions	SECAP	not LCSA related	N/A
D'Orso et al. (2023)	not LCSA related	method development + case study	SECAP	not LCSA related	N/A
D'Onofrio et al. (2023)	not LCSA related	case study	SECAP	not LCSA related	N/A
Dong et al. (2023)	LCA+LCC+S-LCA	compliance analysis	building, construction	10 principles for LCSA	N/A
Leroy-Parmentier et al. (2023)	LCA+LCC+S-LCA	compliance analysis	N/A	10 principles for LCSA	N/A

Conclusions

An increasing number of studies combining LCA, LCC and S-LCS methods to analyse and compare the sustainability performance of different power technologies and solutions improving energy efficiency demonstrates a growing interest in sustainability assessment related to the energy and power sector. However, most of the existing publications present the results of particular indicators separately or conclude with three final results for environmental, economic and social impacts. A number of various methods have been identified to integrate individual LCSA indicators and determine one final score for each scenario being compared, which would be invaluable support for decision-makers in the interpretation phase. Although the methods integrating LCSA results represent different approaches, they often manifest the same common characteristic consisting of assigning certain importance coefficients to individual indicators and assuming the same weight for aggregated scores which express environmental, economic and social effects. The assumption may be considered controversial as system boundaries for LCA, LCC, and S-LCA usually do not overlap in their scope. The other issue is the lack of agreement on the selection and definition of the impact categories to be analysed, which results in incomparable inventory data being processed in different studies. Furthermore, the existing scope inconsistencies may also lead to taking into account some effects twice. Thus, the combining of sustainability indicators still suffers from the lack of harmonisation of the specific procedures applied that would enable reliable results comparison. Some of the methods proposed tend to simplify the relationship between sustainability components, while others develop complex tools to provide outcomes reflecting appropriate proportions of all environmental, economic and social effects. However, the results of both of the approaches seem to be not easy for decision-makers to interpret: the former – given the number of indicators that should be considered, and the latter – due to the difficulty in comprehending the processing of particular effects into the final score.

In conclusion, the integration of LCSA indicators needs further research to reach a consensus on key elements of analyses, including defining system boundaries, selecting the impact categories to be considered and integration procedures. The difference in assumptions made for all sustainability dimensions (e.g. system boundaries) and the importance attributed to them could be considered while assigning the weights to particular impact categories. Adopting solutions known from LCA, as the most developed of the LCSA methods, may also lead to satisfactory findings (weighting procedure expressing all impacts in the same units, application of the mixing triangle or a corresponding multidimensional method that avoids setting specific weights). In the current stage, none of the proposed approaches has a leading position. The development of various integrating methods could be recommended with a perspective of future standardisation.

The contribution of the authors

Conceptualization, A.M. and P.H.; investigation, A.M. and P.H.; literature review, A.M. and P.H.; writing – original draft preparation, A.M. and P.H.; writing and editing, A.M. and P.H.; conclusions, A.M.

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INTEGRACJA WSKAŹNIKÓW OCENY ZRÓWNOWAŻONOŚCI CYKLU ŻYCIA DLA OBSZARU ENERGII

STRESZCZENIE: Pomimo rosnącej liczby badań dotyczących oceny zrównoważoności w obszarze energii, większość istniejących publikacji przedstawia wyniki poszczególnych wymiarów LCSA osobno. Zidentyfikowano szereg metod integracji poszczególnych wskaźników i określenia jednego końcowego wyniku zrównoważoności, które mogą być istotnym wsparciem dla decydentów w priorytetyzacji porównywanych scenariuszy w fazie interpretacji. Na obecnym etapie żadna z proponowanych metod nie wydaje się mieć wiodącej pozycji. Integracja wskaźników zrównoważoności nadal wymaga harmonizacji w zakresie wyboru i definicji kategorii wpływu, które mają być analizowane, jak również konkretnych procedur, które pozwoliłyby na wiarygodne porównanie wyników. Istniejące procedury często zakładają arbitralne określenie współczynników wagowych dla agregowania wyników środowiskowych, ekonomicznych i społecznych, co może budzić kontrowersje. Rozwój bezkontrowersyjnych metod integracji wskaźników LCSA jest rekomendowany również z uwagi na wymogi przyszłej standaryzacji.

SŁOWA KLUCZOWE: wytwarzanie energii elektrycznej, zużycie energii, zrównoważony rozwój, LCA, LCC, S-LCA, LCSA, zarządzanie cyklem życia

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