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LINKED SYSTEM ASSESSMENT TO SUPPORT SUSTAINABLE ENERGY SUPPLIES "LISA"

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Abstract. The globally agreed climate targets require an expansion of renewable energies within the entire supply system. To support this a well-developed set of methods is needed to assess technical, environmental, social, and economic impacts. These methods must cover the entire life cycle and should enable an efficient and target-oriented assessment of energy technologies and systems. The Josef-Ressel (JR) centre LiSA (established 1st January 2022) will address this need. It will develop assessment methods focusing on thermal energy conversion systems embedded in a renewables-rich energy landscape.

Keywords: environmental life cycle assessment (LCA), social life cycle assessment (SLCA), life cycle costs (LCC), life cycle sustainability assessment (LCSA), sustainable energy supply.

Introduction

The Josef-Ressel (JR) centre LiSA targets three system levels 1) single technologies that generate and convert energy to heat/cold (and power), 2) distribution networks for heating and cooling services, 3) integrated energy systems that combine heating/cooling systems with renewable energy sources such as sector coupling technologies. The objective is to adapt and develop methods to provide a dynamic sustainability assessment framework. The framework should be generally applicable to thermal energy systems.

To model and assess different energy systems various methods are used and combined to ensure an overall assessment. The methods we focus on are the environmental life cycle assessment (LCA), the social life cycle assessment (SLCA) and the economic evaluation of life cycle costs (LCC). When combining these three the implementation of a life cycle sustainability assessment (LCSA) will be possible.

Within the paper the goals of the JR- centre LiSA will be presented and a review of state of knowledge concerning LCA, SLCA and LCC applied to thermal energy systems will be discussed.

1. LiSA overview

The objective of the JR- centre is to develop an advanced, dynamic and comprehensive assessment framework for thermal energy transformation technologies and heating and cooling networks in a renewables-rich environment, using concrete application cases and business models that are of interest to the centre's corporate partners, two Austrian regional utilities of Burgenland province and the capital city of Vienna.

To model and assess thermal energy systems, the JR- centre LiSA uses, adapts, and combines the three mentioned methods LCA, SLCA and LCC with technical simulation and optimization of energy systems. The combination of the three system levels – single technologies, distribution networks and integrated energy systems with the four methods forms a conceptual 3×4 matrix (3 system levels × 4 methods) that provides the overarching structure for our JR- entre LiSA (see Figure 1).

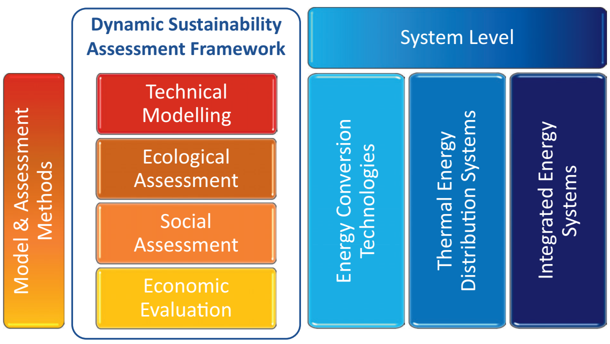

Figure 1. Overall structure of the JR- centre "LiSA". Rows describe the methods to be developed by the centre; columns describe the three categories of method application cases (= three "System Levels")

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The following paragraphs follow the matrix structure of Figure 1, with the literature review on modelling and assessment methods (rows in Figure 1) in Capter 2, and an overview on application on different system levels (the columns in Figure 1) in Capter 3, focusing on energy systems.

2. Overview methods

2.1. Ecological assessment of energy systems (LCA)

Life cycle assessment (LCA), sometimes also referred to as Environmental Life Cycle Assessment, is a well-established, quantitative and systematic method to assess the potential environmental impacts of a product or service over its entire life cycle. In what is sometimes called a "cradle-to-grave" approach, the life cycle consists of four stages, from raw material extraction and acquisition to the production and manufacturing stage, the use stage and finally the end-of-life stage including disposal and recycling. The method emerged in the late 1960s and today it has evolved into the predominant environmental assessment tool (McManus & Taylor, 2015), with a large number of applications in the field of energy systems (Laurent et al., 2018).

The overarching goal of this method is to minimize the emissions of pollutants and conserving non-renewable resources and ecosystems. Due to its quantitative approach, LCA can be used to compare the environmental impacts of different technologies and products, and as such it is well suited to support decisions and policies in the energy sector.

To harmonize the LCA method, it was defined in the 14040 series of international standards – ISO 14040 (International Standard Organization [ISO], 2006a), ISO 14044 (ISO, 2006b), and related standards (Klöpffer & Grahl, 2009). They list four phases in conducting an LCA: 1) Goal and Scope Definition, 2) Inventory Analysis, 3) Impact Assessment and 4) Interpretation.

In the first phase ("goal and scope definition"), the goal of the LCA is defined and the product or service under study is specified. In the second phase ("life-cycle inventory", LCI), a model of the life cycle is built from unit processes and a list is assembled of the resources used and pollutants emitted during the product or service's life cycle. Third, in the phase of "life-cycle impact assessment (LCIA)", the inventory from the second phase is related to a selected list of environmental impacts. In the fourth and last phase ("life-cycle interpretation"), the findings of the previous phases are evaluated in relation to the goal and scope of the study, and conclusions are reached.

2.2. Social assessment of energy systems (SLCA)

Social Life Cycle Assessment (SLCA) is a social or socio-economic impact evaluation method. Its purpose is to assess a product's positive and negative impacts to stakeholders throughout the product's life cycle (Benoit Norris & Mazijn, 2009; Jørgensen et al., 2008; Reitinger et al., 2011). It can serve as a decision support tool for consumers as well as for management and policy makers. The main goal of SLCA results is to assess human well-being, for example individuals' and communities' autonomy, freedom, and fairness. "Human well-being" is the so called Area of Protection (AoP) which is commonly associated with SLCA (Benoit Norris & Mazijn, 2009; Ekener-Petersen, 2013; Jørgensen et al., 2008). Other assessment methods cover different AoPs; for example, LCA can yield scores in the AoPs resources scarcity and ecosystems protection.

To perform a social life cycle assessment, the procedural framework of LCA from the international standards on LCA (ISO, 2006b, 2006a) is usually adopted as a point of departure (Grießhammer et al., 2006). While no universally agreed method for SLCA has been established yet, the most widely known methodological SLCA source is the UNEP/SETAC guidelines for SLCA (Benoit Norris & Mazijn, 2009), with a recent major update (Benoit Norris et al., 2020). The UNEP/SETAC guidelines define five different stakeholder groups with subcategories (Table 1 shows an excerpt) and six stakeholder-related impact categories (human rights, working conditions, health and safety, cultural heritage, governance and socio-economic repercussions).

Table 1. Stakeholder groups and related subcategories according to the social life cycle assessment (SLCA) guidelines, an excerpt (Benoit Norris & Mazijn, 2009)

Stakeholder categories	Subcategories
Stakeholder "worker"	Child Labor; Fair Salary; Working hours; Forced Labour; Equal opportunities; …
Stakeholder "Consumer"	Health & Safety; Transparency; End of life Resonsibility; …
Stakeholder "local community"	Acess to material and immateerial resources; Safe & healthy living conditions; respect of indigenous rights; …
Stakeholder "society"	Public commitments to sustainability; prevention & mitigation of armed conflicts; corruption; technology development; …
Value chain actors* not including consumers	Fair competition; promoting social responsibility; supplier relationships; …

Various indicators have been establish to operationalise these impacts; most of them can be classified as evaluative indicators (Henke & Theuvsen, 2012). Therefore, SLCA cannot be considered a purely quantitative evaluation method.

2.3. Economic assessment of energy systems (LCC)

Life Cycle Costing (LCC) summarizes all costs of products and systems over their entire life cycle that are directly connected to one or more actors involved in the life cycle (Zamagni et al., 2016; Hunkeler et al., 2008). In an LCC analysis, all phases in the life cycle of a product system should be taken into account, i.e. from the conception and raw material extraction to production and use to disposal. LCC is suitable as an instrument to make all costs associated with a product system visible. In an LCC, costs are defined as real cash flows reflecting the economic value of products and services (Zamagni et al., 2016).

The Environmental LCC (ELCC) is an LCC method that was developed out of the need for a formalized, standardized set of rules for the economic part of a sustainability assessment (Hunkeler et al., 2008). The addition "Environmental" indicates that the ELCC should be carried out consistently with the ecological analysis (LCA) according to recognized methods (e.g. ISO 14040 (2021)), (Heijungs et al., 2013).

2.4. Life-cycle sustainability assessment of Energy systems (LCSA)

The present state of the art in life-cycle sustainability assessment has recently been reviewed by Visentin et al. (2020), and – more specifically for energy technologies – by Buchmayr et al. (2021). Most approaches combine three assessment methods form the „triple bottom line" of sustainability assessment (Klöpffer & Renner, 2007):

- life cycle assessment (LCA), where environmental impacts are examined in more detail, based on the ISO 14040 (ISO, 2006a) family of international standards.
- life cycle costing (LCC), which is also based largely on elements of the LCA method described the ISO 14040 (ISO, 2006a) family; it frequently ignores external costs to avoid double counting of environmental burdens, which are already covered by LCA.
- social life cycle assessment (SLCA), where social impacts are considered, also incorporates elements of the ISO 14040 (ISO, 2006a) family, but in contrast to the previous two methods it includes positive and negative social impacts on stakeholders throughout the product's life cycle.

Life cycle sustainability assessment (LCSA) as a framework (Klöpffer, 2008; Guinée et al., 2011; Heijungs et al., 2010; Zamagni et al., 2016) combines these dimensions, ideally within the same system boundaries (1):

$$LCSA = LCA + LCC + SLCA. \tag{1}$$

Exactly how LCA may be combined with other methods towards a sustainability assessment may depend strongly on the specific application and the user's objectives (Jeswani et al., 2010). A particular challenge to an LCSA is the fact that LCA, SLCA and LCC are not evenly advanced from a methods point of view (Neugebauer, 2016): only the LCA method has its own international standard. Additionally, in contrast to LCA, SLCA does not have established impact category definitions, and for LCC the impact level is not defined at all.

In Alejandrino et al. (2021) existing LCSA studies were reviewed in order to check how the three dimensions of sustainability (see Eq. (1)) come together and how the different methods were applied. An important question was how methods work consistently to each other and if it's possible to deliver consistent results. Major divergences were found in the economic and social assessment – very often not all stakeholders or value chain actors were considered. The literature on the question of how to combine indicator results is substantial, but not necessarily with a focus on thermal systems. Specifically for energy systems, Martin-Gamboa et al. (2017) reviewed 62 papers on different multi-criteria decision analysis (MCDA) methods for sustainability assessment. However, only five studies dealt explicitly with thermal energy systems. Methodologically, the authors selected a combination of life cycle approaches (including LCA, SLCA) with Data Envelopment Analysis as a promising framework for a sustainability assessment of energy systems that can facilitate decision-making and energy planning.

3. Overview system level application

The application of different assesement methods is topic of various studies concerning energy systems, but especially LCSA and LCC are very rare. LCAs of thermal technologies and systems are numerous, and therefore the review in this and the following two sections covers only a few examples of thermal conversion technologies, district heating LCAs and LCAs of integrated systems that will be of particular interest to our research.

3.1. Energy Conversion Technologies

– LCAs

Heat pumps as thermal energy conversion devices have been studied extensively in LCA literature. Knobloch et al. (2020) investigated the global net climate impact of making heat pumps the dominant residential heating sector, using three scenarios through 2050 with an integrated assessment model at regional resolution. They found that – even in the worst case of a barely decarbonized global electricity sector – heat pumps are likely to reduce overall greenhouse gas emissions relative to continued fossil-based residential heating. Several LCA studies (G. Li, 2015; Mattinen et al., 2015; Staffell et al., 2012) confirm the significance of electricity mix for the overall environmental impacts for the climate effects of heat pumps, in contrast to a relatively minor contribution from climate-active refrigerant losses. Two additional studies point out the relevance of using temporal resolved electricity mixes when running heat pumps (Frapin et al., 2022) and (Peters et al., 2022). Frapin et al. (2022) shows that the environmental impacts vary more deeply on the different scenarios of electricity mixes than on the type of building. In Peters et al. (2022)we see a noticeable difference when using an average electricity generation mix compared to the marginal generation mix. Also, hourly and monthly emission factors were determined which has a high relevance when assessing systems.

Several LCAs study a combined system: a heat pump combined with a solar energy source; an overview is provided by Longo et al. (2017). Eicher and colleagues (Eicher et al., 2014) compared life-cycle non-renewable energy use (based on monthly simulations) and climate change impacts for solar-thermal assisted heat pumps, conventional ground-based heat pumps, and a combination of solar-thermal and heat pump heating. The latter option showed the lowest climate change impacts when the electricity was supplied with the average European electricity mix. The authors also emphasize the importance of the electricity mix for the overall heat pump impact, causing up to 75% of total climate change contributions. A study by Longo et al. (2017) uses the TRNSYS simulation software to model and optimize the operation of an adsorption chiller for residential cooling. These simulations provide energy balances for an LCA comparison with a conventional, photovoltaics-fed compression chiller/heat pump. In most cases, the conventional, compression chiller system has a lower energy use and climate impact. A similar LCA by Shirazi et al. (2017) modelled solar-assisted absorption heat pumps. The authors conducted a simulation-based multi-objective optimization of three different solar-powered absorption chiller designs with respect to energy, environmental and economic metrics. Using TRNSYS and MATLAB to find Pareto optimal solutions, they conclude that energy use and climate impacts are reduced relative to a conventional system, but that costs are not competitive. The significance of these last two studies lies in the combination of a technical system simulation and optimization, with a life-cycle assessment approach (Figure 2).

– SLCAs

It is difficult to find studies that deal specifically with SLCA in the context of thermal power technologies or distribution systems. One of them is Martín-Gamboa et al. (2021) using the SLCA methodology to compare two biomass-to-electricity power plants located in Portugal. For this purpose, a fluidised-bed system was compared with a grate furnace system. Six indicators were used for the social evaluation (child labour, forced labour, gender wage gap, women in the sectoral labor force, health expenditure, and contribution to economic development). The authors come to the conclusion that the use of the more efficient fluidised-bed furnace system could result in a "reduction of 15–19% in all the evaluated negative social impacts (with the exception of women in the sectoral labour force)". The Study highlights also the supply chain areas with the highest social risks.

In addition to this study, which looks at the social impact of thermal energy systems, there is another study that looks at the social impact of an electrical energy system. Lehmann et al. (2022) propose a way of assessing the social impact of offshore wind farms from the perspective of the company where in addition to indicators such as child labor, the local community and acceptance are also considered.

– LCCs

LCC studies on single energy systems (Ranganath & Sarkar, 2021; Traverso et al., 2012) as well as building-LCC's which also take into account the respective energy system integrated in the building (Gu et al., 2008; Liu et al., 2016) were found. In the case of the building LCC's comparative analysis of the renovation of listed and non-listed buildings was conducted. The observed heating systems were a wood fired system, a groundwater heat pump and a district heating connection (Gu et al., 2008).

3.2. Thermal Energy Distribution Systems

– LCAs

There are many LCA studies of thermal energy distribution networks, typically of district heating networks.

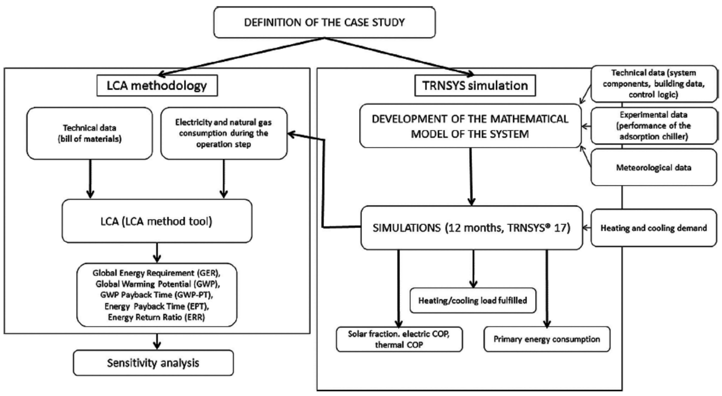

Figure 2. Combining technical optimization (TRNSYS simulation, right-hand side) with an environmental life-cycle assessment (LCA, left-hand side) for an integrated energy system (Longo et al., 2017)

A review of district heating and cooling systems by Lake et al. (2017) also discusses their environmental impact and economic feasibility. Other studies also discuss relevant LCA literature (Diaz et al., 2020; Ravina et al., 2017). These works typically include the various heat sources, which dominate the overall environmental impacts, and a very limited selection is discussed in the subsequent chapter on integrated systems. The infrastructure of the district heating network itself is not the focus of these studies. An exception is a series of three papers (Fröling et al., 2004; Fröling & Svanström, 2005; Persson et al., 2006) that provides information on the entire system – pipe production, network construction and the use phase as well. In a related study by the same group (Perzon et al., 2007), the authors assess an existing district heating network including substations; they find that the main environmental impacts of the network are due to extra heat production (biomass combustion emissions) that is needed to compensate for the network's heat losses. Koefinger et al. (2016) compared four low-temperature district heating systems in Austria. As is planned in the centre, the authors simulated the thermo-hydraulic behavior with Modelica/Dymola software, and processed results to determine indicators for the systems' energy, climate change and economic performance. They found that dynamic calculations are necessary because of the complex and dynamic system elements, and that optimum system design and operation are highly dependent on local conditions. In particular, the availability and pricing of low-temperature heat sources is critical to a network's economic feasibility.

– SLCAs, LCCs

No studies were found that specifically address SLCA in the context of thermal energy technologies or distribution systems; social assessments – if conducted at all – are mostly part of an LCSA study. Also no studies with special focus on LCC of thermal energy distribution systems were found.

3.3. Integrated Energy Systems

– LCAs

An overview by Lund et al. (2014) argues that sector coupling between renewable energy sources and new (4th generation) smart district heating and cooling systems is key to a future, more sustainable non-fossil heat supply. Prospective studies of future renewables are particularly important for LCA models that couple renewables with thermal systems. For example, Arvidsson et al. (Arvidsson et al., 2018) list prospective LCAs of wind turbines and photovoltaics.

Several LCA studies address the issue of the lowest-impact heat source and design for integrated district heating (and cooling) systems. Hammar and Levihn (2020) assess time-dependent climate impacts of adding a large biomass CHP plant that substitutes marginal power to the district heating system of Stockholm, as a function of different fuels. Dynamic changes of both biomass growth and the district heating system itself are modelled over 35 years into the future. Result show that wood chips as a CHP fuel result in much lower climate impacts for the entire system than the use of solid waste as a fuel. Bartolozzi et al. (2017) modelled a small district heating and cooling network in Italy. They compared three different heat sources (geothermal heat-pump, biomass combustion, and natural-gas combustion), as well as a decentralized system with gas boilers and air-air heat pumps for cooling. heat source. Relative to the natural-gas supplied network, climate change impacts were approximately 35% and 20% lower for the geothermal system and the biomass system, respectively. The decentralized system had the highest impacts.

The comparison of integrated central thermal systems with decentralized single-building systems is also the topic of several related LCA studies that generally find advantages for the integrated system, often depending on the local availability and economics of renewables: Guarino et al. (2020) used TRNSYS simulations and LCA to compare the environmental impacts of two residential heating and cooling scenarios in a hypothetical small, energy-optimized Canadian neighbourhood: An efficient conventional system that uses individual heat pumps for both heating and cooling, and a solar-thermal assisted district heating network with seasonal thermal storage. The solar district heating system had lower environmental impacts than the conventional system for all categories quantified, with reductions of 39–56% for most.

– SLCAs

SLCA studies of integrated thermal energy systems as such were not found in literature, possibly due to a lack of data on social indicators of upstream supply chains (Pucker-Singer et al., 2020). Energy-related SLCA in a wider sense often use indicator values at national scales. For example, Goers et al. (2020) evaluated the positive effects on employment levels and the gross domestic product due to a transition to a renewable energy supply in Austria. For electricity generation, social indicators were developed in a discursive process as part of the NEEDS project (Gallego Carrera & Mack, 2010). A set of social indicators were developed and verified by stakeholders; the rating of technologies for each indicator was through expert judgment. The authors present several indicators which belong to four overarching criteria: "security and reliability of energy provision", "political stability and legitimacy" and "social and individual risks" and "quality of life". The relevance of these criteria and their associated indicators was tested by stakeholder surveys and a Delphi group method.

– LCCs

The research situation is not very diverse in LCC studies on integrated energy systems, only two studies of this type were found (Paiho et al., 2017; Ristimäki et al., 2013).

Investors often have concerns that ecologically sustainable investments would perform worse economically (Naves et al., 2019). Here LCC plays an important role because combined LCA and LCC analyses can show when economic and ecological sustainability go hand in hand.

4. Overview life cycle sustainability assessment (LCSA)

Atilgan and Azapagic (Atilgan & Azapagic, 2016) presented an LCSA of electricity-generating technologies in Turkey, considering environmental, economic and social aspects. They identified geothermal sources as low-impact from an environmental perspective, but costs were highest of all sources. In contrast, gas power has the lowest capital costs of the energy technologies considered, but from a social perspective it provides the least employment opportunities with high levelized costs and ozone layer depletion. For the use of building managers, Luong et al. (2012) presented a sustainability assessment framework for renewable energy technologies see Figure 3. In contrast to most LCSA work that adopts the triple bottom line perspective, the authors added the technical criteria of performance, durability, and flexibility/adaptability to their framework.

J. Li et al. (2023)reviewed more than 70 studies regarding the assessment of geothermal power plants according to the LCSA approach. They concluded that the few existing studies focused on the environmental impacts, whereas the levelized cost of electricity was often used for the assessment in the economic analysis. With regard to social evaluation, social acceptance has often been chosen as an indicator.

No example was found for sustainability assessments that focus on district heating and cooling networks by themselves. However, a number of integrated system studies involve district heating systems, for example Kontu et al. (2015). Ghafghazi et al. (2010) ranked energy sources (natural gas, wood pellets, sewer heat, and geothermal heat) for a district heating system in Canada, based on six criteria, using the Analytic Hierarchy Process (AHP) method. The study did not include social criteria. Wood pellets were identified as the best alternative

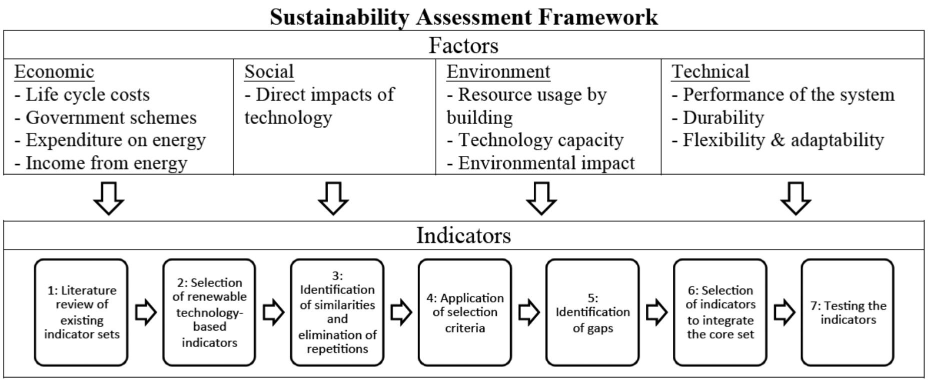

Figure 3. Sustainability assessment framework for renewable energy technologies (Luong et al., 2012)

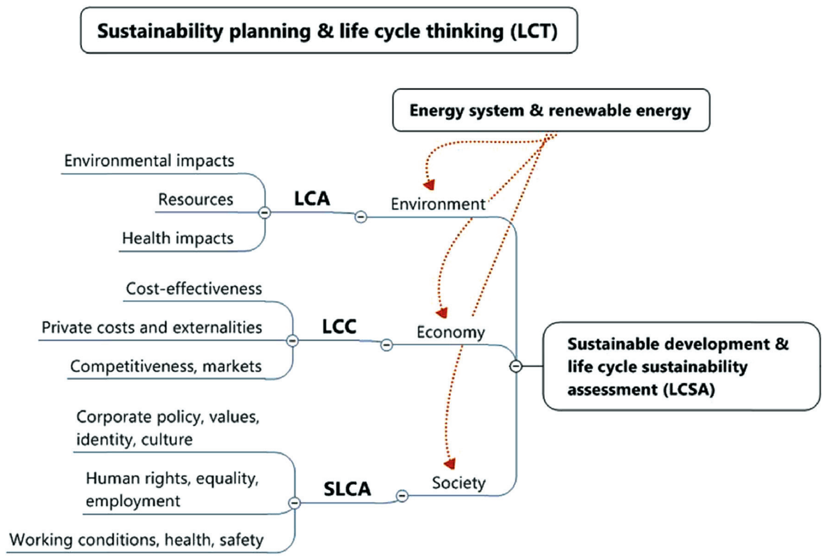

Figure 4. LCSA framework ap-plied to a generic energy system.
On the left: impact endpoints of the single assessment methods LCA, LCC, SLCA (Mälkki & Alanne, 2017)

for all stakeholders, if efficient communication about stakeholder concerns was ensured. Chen et al. (2020) conducted a quantitative sustainability assessment of a district heating system, coupled with a geothermal heat pump, photovoltaic power, and a solar thermal collector. They calculated a composite sustainability index for such hybrid systems, using an information entropy method to weigh and aggregate eleven individual indicators on energy, environmental (air pollutant), economic and societal (employment) impacts.

Figure 4 gives an overview of an LCSA framework for energy systems and renewable energy (Mälkki & Alanne, 2017), with suggested endpoint impacts for each method.

Conclusions

Reviewing the studies a conclusion for developing an approach within the JR-centre LiSA is that a wide variety of indicators is necessary for a sustainability assessment of energy technologies. To find the most meaningful is clearly an important goal.

In contrast to most LCSA studies, to add various technical criteria like performance, durability, and flexibility to a framework is a valuable add on. With the LiSA approach it has to be evaluated how to added technical criteria to the triple bottom line perspective.

Another big issue is to conduct dynamic calculations. This is necessary because of the complex and dynamic system elements of integrated energy systems. The optimal system design, the best operation is highly dependent on local conditions over time.

The literature review also showed several methodological deficits, as there are no uniform frameworks or standards, the database still needs improvement especially on information on upstream chains for SLCA and LCC data. In the case of SLCA the social acceptance has often been chosen as an indicator, which is an important topic beyond the standard SLCA Indicators from the existing framework.

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Disclosure statement

The authors declare that there are no competing financial, professional, or personal interests from other parties.

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