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REVIEW

Systematic literature review on the application of life cycle sustainability assessment in the energy sector

T.E.T Dantas[1] · S.R Soares[1]

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Abstract
Life cycle sustainability assessment (LCSA) is an assessment method capable of supporting decision makers toward a more sustainable system. In this paper, a systematic literature review regarding LCSA application in the energy field was performed. The main challenges, methodological approaches, and sustainability indicators used to perform LCSA studies in this sector were highlighted. Peer-reviewed articles published until December 2020 were considered. The research portfolio consisted of 34 publications. According to the results, the energy sector functions as a platform for LCSA application and methodological development, as the number of studies applying this methodology in energy-related systems grew exponentially over the years. The review suggests that the choice of the life cycle concepts (system boundary, impact categories, etc.) is a critical point, as basically, every study presented different characteristics of life cycle studies. An even bigger diversity regarding sustainability indicators was found, especially regarding the social and economic pillars. A trend in the application of multi-criteria decision analysis (MCDA) to integrate results and facilitate decision- and policy-making processes was identified. Future studies could focus on the integration between LCSA other methods, identify solutions for the system boundaries interaction across sustainability dimensions, and develop further case studies, specially by combining LCSA and MCDA.

Keywords Sustainability · Energy · Energy sector · Life cycle sustainability assessment · Life cycle thinking · Systematic literature review

Abbreviations

CED	Cumulative energy demand
CExD	Cumulative exergy demand
CLCD	Chinese life cycle database
DEMATEL	Decision-making trial and evaluation laboratory
FU	Functional unit
GRA	Gray relation analysis
LCA	Life cycle assessment

✉ T.E.T Dantas
thalestavaresd@gmail.com

[1] Department of Sanitary and Environmental Engineering, Life Cycle Assessment Research Group (CICLOG), Federal University of Santa Catarina (UFSC), Florianopolis 88040-970, Brazil

LCC	Life cycle costing
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
LCSA	Life cycle sustainability assessment
LCSAnalysis	Life cycle sustainability analysis
LCSD	Life cycle sustainability dashboard
LCT	Life cycle thinking
MADA	Multi-attribute decision analysis
MAVT	Multi-attribute value tree analysis
MCDA	Multi-criteria decision analysis
MRIO	Multi-regional Input–Output model
SDG	Sustainable development goals
SETAC	Society of Environmental Toxicology and Chemistry
SHA	Social hotspot analysis
SHD	Social hotspot database
SLCA	Social life cycle assessment
SMAA	Stochastic multi-criteria acceptability analysis
TOPSIS	Technique for order of preference by similarity to ideal solution
TBL	Triple bottom line
UNEP	United Nations Environmental Program
VIP	Variable interdependent parameters analysis
WIOD	World Input–Output Database

1 Introduction

Along with the pressing population growth comes the need for cleaner, renewable, and affordable energy for all (de Souza Junior et al., 2019; IEA 2020). As electricity grew to be a fundamental commodity in our society, it pushed the energy sector to the center of social progress and economic prosperity (World Bank, 2017). In light of the importance given to this sector in the pursuit of tackling intergenerational and global issues such as climate change (IEA 2019), circular economy (EMF 2019), and energy scarcity (World Energy Council 2020), the Sustainable Development Goal (SDG) Number 7 was created and incorporated to the United Nations Agenda 2030 (Sachs et al., 2019). Since energy systems play a decisive role in the overall growth and development of nations, a sustainable approach to energy systems can improve the economy, social well-being, and the reduction of general environmental impacts (Maxim, 2014). Considering the complex and interdependent nature of the energy industry, a comprehensive way for assessing impacts through a systematic lens is critical to enable effective decision and policy-making toward achieving the targets set in SDG 7, and ultimately, promote sustainable energy production.

Life cycle sustainability assessment (LCSA) is an extensive assessment method used to support decision-making processes toward sustainable solutions. Rooted in the conceptual basis of life cycle thinking (LCT), it gained the attention of the scientific community in the last decade (Zimek et al., 2019), especially after the publication of the UNEP/SETAC LCSA guidelines (Ciroth et al., 2011). By adopting a view on sustainability based on the triple bottom line (TBL) (WCED 1987), the LCSA framework envisions delivering sustainable solutions and decision-making options in a balanced manner (N.C. Onat et al., 2016). In LCSA, the evaluation of the environmental extent of sustainability is carried through life cycle assessment (LCA), a well-established and standardized methodology developed to address the impacts of services and products based on a life cycle approach (ISOa 2006). The social and economic counterparts of LCSA are performed through two methodologies that follow LCT's viewpoint. Social life cycle assessment (SLCA) is used to identify and analyze social repercussions, while life cycle costing (LCC) focuses on the financial sustainability of the addressed system. Although LCSA is a growing trend, the development of its theoretical backbone and research toward its operationalization in different sectors is still ongoing (Sala et al., 2013).

The LCSA framework has been employed to examine the sustainability of recycling systems (Hu et al., 2013), livestock (de Boer et al., 2011), additive manufacturing (Ribeiro et al., 2020), petrochemical industry (Maleki et al., 2020), housing (Janjua et al., 2019), and many other industrial sectors. However, the energy field features as the segment targeted by most researchers (Costa et al., 2019). The broadness and importance of this sector for sustainable development create a scientific hotspot between the already trending LCSA scientific explorations and the pursuit for better technologies and methodologies to drive society toward the SDG 7 targets.

In that context, this study systematically reviews energy-related LCSA literature. Based on the current trend of LCSA methodological development and case studies, this paper envisions highlighting the main challenges, methodological approaches, definitions, and sustainability indicators used to perform LCSA studies in the energy sector. This choice is made on fact that the energy sector, due to its integrative nature, is closely linked to all other sectors of industry and service provisions. Therefore, by shining light on the sustainability explorations regarding this broad sector, the authors aim to support practitioners in further investigations regarding this scope and aid in the run to reach the targets set in SDG 7. As far as the authors are aware, this is the first analysis focused on LCSA energy-related studies. The only other study that performed an LCSA systematic literature review focused on a specific sector was the work of Tarne et al., (2017), directed to the automobile industry. Therefore, the innovation of this study lies in the crossroads between LCSA methodological development and the changeover to a cleaner and sustainable energy sector.

2 Background

LCSA is a multilateral assessment method developed to support decision makers in analyzing the best options for a specific system while weighing the three dimensions of sustainability—environmental, economic, and social. Centered on LCT (Zimek et al., 2019), LCSA commonly takes a cradle-to-grave approach to determine the impacts that a product may cause throughout its life cycle. This methodology gained attention circa twenty years ago, in which the work of Kloepffer, (2008) and Finkbeiner et al., (2010) solidified LCSA as a promising scientific field. Later on, Guinée et al., (2011) even judged it to be the "future of LCA," in which the 2010–2020 decade would be critical, as LCSA would help the establishment of a comprehensive set of mechanisms to address sustainability issues at various scales.

The technical base of LCSA is LCA, an assessment method standardized by the norms ISO 14,040 (ISOa, 2006) and ISO 14,044 (ISOb, 2006), created to identify environmental hotspots at different life cycle stages of products or services (de Souza et al., 2020). Research in integrating the social (Dreyer et al., 2006; Hunkeler, 2006; Norris, 2006) and economic extents (Klöpffer, 2003; Rebitzer & Hunkeler, 2003; Weidema, 2006) to the already well-established environmentally focused LCA gained numbers in the early 2000s.

The economic equivalent of LCA is LCC, proposed to take into account indirect costs and externalities of a product's life cycle (Klöpffer, 2003). Thus far, different options have been drawn concerning the level of completeness from LCC. Some researchers judge it to be a consolidated method (Sureau et al., 2018); others affirm that it has not yet achieved its full maturity (Dong & Ng, 2016; Martínez-Blanco et al., 2014). The second opinion is supported by the fact that differently from LCA, LCC has no standardized norm, just a code of practice that works as a guideline for practitioners (Swarr et al., 2011).

Concerning the social pillar of sustainability, SLCA is the life cycle-based methodology used to address the social repercussions of a production system based on the LCT's rationale. Similar to LCC, this method also lacks a standardized norm such as the ISO 14,040 and ISO 14,044, which provide structuring directives and orientations regarding the development of LCAs. However, it has a specific guideline document developed by UNEP/SETAC (Benoît et al. 2013) that intensely helped in the dissemination of the topic (Costa et al., 2019; Sureau et al., 2018). Nonetheless, SLCA still falls behind as the least developed methodology between its pairs due to operational challenges, for example, the use of databases (Social Hotspot Database, PSILCA database, etc.), the definition of indicators, choice of stakeholders analyzed, relation to the function unit selected (Petti et al., 2018; Wu et al., 2014; Wulf et al., 2019).

As pointed out by different authors (Costa et al., 2019; Tarne et al., 2017; Wulf et al., 2019), the most widely applied LCSA approach was established by Kloepffer (2008), in which calculations are carried out as described by Eq. 1:

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

According to the same authors, the main prerequisite for this approach is consistency regarding the system boundary choice. As mentioned by recent publications, this is a still ongoing challenge of LCSA (Costa et al., 2019; Heijungs et al., 2010; Wulf et al., 2019). To go around such a problem, alternative approaches have emerged. Kloepffer (2008) proposed a second viewpoint at LCSA, one in which LCC and SLCA are handled as additional impact categories in Life Cycle Impact Assessment (LCIA), relying therefore on the same inventory. A third approach, life cycle sustainability analysis (LCSA), combines LCI and LCIA phases in a single modeling phase (Guinée et al., 2011). Further attempts to develop methodological procedures followed, mainly by proposing the sum of LCA with another cluster of sustainability-relevant aspects, such as eco-efficiency or socioeconomic analysis (Costa et al., 2019), or by taking the Input–Output LCA methodology and applying it to LCSA (Onat et al., 2014). To this day, novel approaches and frameworks are being developed (Gumus et al., 2016; Ren & Toniolo, 2018). However, the publication of LCSA guidelines and methodological sheets by UNEP/SETAC (Ciroth et al., 2011) contributed to the dissemination of the LCSA approach described by Eq. 1 as the preferred approach by practitioners (Costa et al., 2019; Tarne et al., 2017; Wulf et al., 2019), and further development of the method.

Currently, LCSA development faces different challenges. Reviews and state-of-the-art publications suggest that the absence of harmonization between LCA, LCC, and SLCA is the main setback faced by this methodology (Costa et al., 2019; Tarne et al., 2017; Wulf et al., 2019; Zimek et al., 2019). The LCSA framework is commonly seen as too broad (Zimek et al., 2019), which translates into the lack of definition in basic LCT aspects (i.e., system boundaries, impact categories, etc.) leading to methodological disparities that may hinder comparative analysis between studies (Costa et al., 2019). Another common topic is the employment of Multi-criteria Decision Analysis (MCDA) to enhance the communication of results (Costa et al., 2019; Zimek et al., 2019). That practice is still seen as controversial, as it opposes the recommendation described in the UNEP/SETEC methodological sheets (Ciroth et al., 2011). Furthermore, publications in the LCSA area seem to reach a consensus when affirming that case studies in different sectors are necessary to shed light on the challenges faced by LCSA development.

3 Materials and methods

According to Fink (2005), a literature review is a systematic and reproducible study design to identify, evaluate, and interpret the existing body of scientific publications. Moreover, this type of study provides an overview of a research topic and helps researchers develop conceptual content regarding a specific scientific area (Meredith, 1993.). Therefore, due to the exploratory nature of this work, based upon the systematic evaluation of the content found in several scientific literature sources, this paper is categorized as a systematic literature review.

This study proposes a comprehensive analysis of LCSA in the energy sector. In this paper, the broad term "energy sector" relates to all activities involved in the fuel exploitation, storage, production, transportation, and distribution of energy. Therefrom, the authors conducted a systematic literature review based on the preferred reporting items for systematic reviews and meta-analyses (PRISMA) guidelines (Moher et al., 2009), aiming at solely peer-reviewed articles. The literature review was carried aiming at the following research questions and the four-step procedure illustrated in Fig. 1.

RQ #1 Has the application of LCSA in energy-related studies progressed over time?

RQ #2 What are the predominant life cycle features used to execute LCSA studies in the energy sector?

RQ #3 What are the major challenges in conducting LCSA studies in the energy sector?

3.1 Identification and screening

This initial phase of the literature review procedure was based on the three research questions mentioned in Sect. 3. The search was conducted through the combination of such keywords using Boolean operators (AND/OR). The search string applied to the scientific databases was:

(("Life Cycle Sustainability Assessment" OR "Life Cycle Sustainability Analysis" OR "Life Cycle Sustainability A*" OR "LCSA") AND ("energy" OR "energy sector" OR "electricity" OR "electricity generation")).

Two extensive article databases were used to conduct the literature search: Scopus and Web of Science. That choice was made based on the comprehensiveness and high access incidence in scientific and academic fields that such databases present (Zanghelini et al., 2016). Both these databases are widely applied in systematic literature review studies (de Oliveira et al., 2019; Costa, 2019; Petti et al., 2018), reinforcing the broadness and robustness needed for such a study.

Identification procedures were carried for "topic" in the Web of Science database and "title, abstract, and keywords" in the Scopus database. Searches led to the detection of 150 peer-reviewed documents. Duplicates (publications found in more than one of the

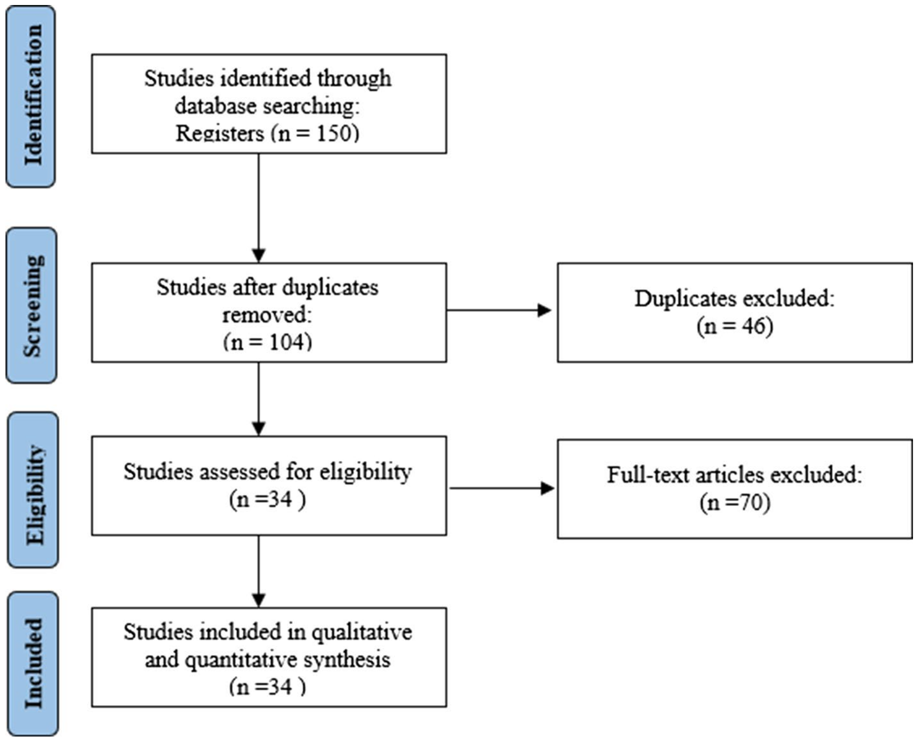

Fig. 1 Literature review procedure, according to the PRISMA guidelines (Moher et al., 2009)

databases during the screening process) accounted for 46 excluded publications, leaving 104 documents remaining (Fig. 1).

3.2 Eligibility

The selection of eligible publications was based on a full reading of the remaining articles and their adherence to the search criteria presented in Table 1.

The main inclusion criteria regarded the application of LCSA methodology. Irrespective of which LCSA approach was employed, only studies that addressed the three dimensions of sustainability through LCT-related methodologies were selected. Publications that focused on only one (i.e., environmental assessment through LCA) or two sustainability dimensions (i.e., socioenvironmental, a combination of LCA and SLCA, etc.) were

Table 1 Screening criteria adopted for article selection

Inclusion criteria	Exclusion criteria
LCSA methodology	Papers addressing only one or two dimensions of sustainability
Energy sector related	Conference papers, books, gray literature
	Non-English written articles
	Duplicates

excluded. This approach aims to give greater reliability in the inclusion of LCSA-related articles. Furthermore, all selected papers present a direct link to the energy field (i.e., electricity generation, electric vehicles, fuels, etc.). Articles that did not have an energy-related focus were excluded.

Explorations aimed solely at peer-review articles published in scientific journals written in English. Books, conference papers, reports, and other forms of gray literature were ruled out of this analysis since they might provide incomplete and still unchallenged findings (Adams et al., 2017; Dantas, 2021). Within this scope, only articles published until December/2020 are analyzed in this study.

The further screening was carried through the full reading of the persisting articles, which lead to the exclusion of an additional 70 publications (Fig. 1). The final portfolio analyzed in this study consists of a group of 34 articles that applied any form of LCSA in the energy sector.

3.3 Content Analysis

The final portfolio was organized through Endnote® software and moved to a spreadsheet for further analysis (for the final portfolio, please refer to the Supplementary Material). The portfolio was organized based on bibliometric information (authors, year of publication, title, and journal) and the classification of articles between case studies, reviews, methodological development, and mixed approached papers (methodological development combined with a case study).

The findings of this review are introduced in Sect. 4. First, results regarding the research protocol implementation are displayed, subsequently followed by the presentation of publication trends. Next, the selected articles are analyzed and discussed according to the research questions.

4 Results

A total of 34 articles were selected after the application of the review protocol and the screening process. Table 2 displays the list of selected publications along with its main characteristics and definitions, which are examined later in Sect. 4.3

The first column of Table 2 shows the reference to each of the 34 studies analyzed in this paper. The second column refers to the choice of the function unit, i.e., a reference to which the inputs and outputs can be related to the function of the analyzed study (ISO, 2006a). The column "system boundary" refers to whether or not the methodological boundaries of the study were explicitly shown in the study. The "software" and "database" columns inform what software and which LCA databases were used in the assessment (when communicated). The sixth column, "LCIA method," refers to what impact method was chosen by each article. The last three columns, "Allocation, "Aggregation/MCDA," and "Sensitivity Analysis," inform the reader if the authors of the publications applied any of these non-obligatory life cycle definitions were applied in the articles.

4.1 Bibliometric results and publication trends

Publication trends were evaluated according to the evolution of LCSA-related articles in the energy sections over the years, the geographical distributions of the author (based on

Table 2 Main characteristics of the analyzed publications

Article	Functional Unit	System Boundary	Software	Database	LCIA method	Allocation	Aggregation/MCDA	Sensitivity Analysis
(Hoque et al., 2020)	Vehicle kilometer travel (VKT)	X	SimaPro 8.4	n/a	n/a	n/a		
(Onat et al., 2020)	One kilometer (km) of Vehicle travel	X	n/a	EXIOBASE 3.4	n/a	X	MADA	
(Guarino et al., 2020)	46-kW thermal Power biomass smoke tube boiler	X	n/a	ecoinvent, Buwal, ELCD	ILCD 2001	n/a		X
(Aberilla et al., 2020)	n/a	n/a	GaBi 7.3	ecoinvent	ReCiPE 1.08 method	n/a	VIKOR	n/a
(Cerrato and Miguel 2020)	n/a	X	n/a	ecoinvent	ILCD 2011 and ReCiPe 2016 1.03	n/a	n/a	n/a
(Guo et al., 2020)	1 kW of electricity generated	X	GaBi	ecoinvent, CLCD	CML2015	n/a	MAVT	n/a
(Collotta et al., 2019)	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
(Corona & San Miguel, 2019)	1 MWh of electricity	X	SimaPro 8.0.3	ecoinvent 3, SHD	ReCiPe, CED 9, Water stress index	X	Sustainability crown	n/a
(Hoque et al., 2019)	Vehicle kilometers travelled (VKT)	X	n/a	n/a	n/a	n/a	n/a	n/a
(Kabayo et al., 2019)	1 MWh of electricity	X	SimaPro 8.0	ecoinvent 3.0	ReCiPe, AWARE, and Usetox 1.04	n/a	n/a	X
(Onat et al., 2019)	Travel distance of 1 km	X	n/a	EXIOBASE 3.41	n/a	n/a	n/a	X
(Roinioti & Koroneos, 2019)	1 kWh of electricity	X	Gemis 4.9.5	Gemis	n/a	n/a	MAVT	X
(Valente et al., 2019)	1 kg of hydrogen with 99.9% purity	X	n/a	PSILCA	n/a	n/a	n/a	n/a

Table 2 (continued)

Article	Functional Unit	System Boundary	Software	Database	LCIA method	Allocation	Aggregation/MCDA	Sensitivity Analysis
(Vogt Gwerder et al., 2019)	1 kWh of electricity and 1 MJ of heat generated	X	n/a	ecoinvent 3.0	IPCC 2013, CED, ReCiPe and Usetox	n/a	MAVT, SMAA, VIPA	n/a
(Wang et al., 2019)	Travel distance of 1 km	X	GaBi	GaBi database	CML2001	n/a	TOPSIS	X
(Ekener et al., 2018)	n/a	n/a	GaBi	ecoinvent	Recipe, CExD	X	MAVT	X
(Li et al., 2018)	Unit of electricity produced by solar PV system	X	GaBi	ecoinvent 3.0	CML 2001, ReCiPe	n/a	n/a	X
(J. Ren, 2018)	n/a	n/a	n/a	n/a	n/a	n/a	TOPSIS	X
(Jingzheng Ren & Toniolo, 2018)	n/a	n/a	n/a	n/a	n/a	n/a	DEMATEL	X
(Akber et al., 2017)	1 kWh of electricity generated	X	SimaPro 8.2.3.0	ecoinvent 3.3	CML-IA 3.03	n/a	Single score aggregation	n/a
(Nguyen et al., 2017)	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
(Azapagic et al., 2016)	n/a	n/a	n/a	n/a	n/a	n/a	MADA	n/a
(Atilgan & Azapagic, 2016)	1kWh of electricity generated	X	GEMIS 4.8, GaBi 6	ecoinvent 2.2	CML2001	n/a	MAVT	X
(Galán-Martín et al., 2016)	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
(Gumus et al., 2016)	n/a	n/a	n/a	n/a	n/a	n/a	TOPSIS	n/a
(Yu & Halog, 2015))	1 kWh of electricity generated	X	SimaPro 7.3	ecoinvent 3.1	CML 2 baseline 2000 2.05	X	LCSD	X
(Onat et al., 2014)	Travel distance of 1 mile	X	EIO-LCA	WIOD	n/a	n/a	n/a	n/a

Table 2 (continued)

Article	Functional Unit	System Boundary	Software	Database	LCIA method	Allocation	Aggregation/MCDA	Sensitivity Analysis
(Santoyo-Castelazo & Azapagic, 2014)	Annual electricity generation in 2050	X	n/a	ecoinvent	CML2001	n/a	MAVT	X
(Stamford and Azapagic 2014)	n/a	X	n/a	ecoinvent	n/a	n/a	Summed-rank analysis	X
(Bachmann, 2013)	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
(Manzardo et al., 2012)	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
(Stamford & Azapagic, 2012)	n/a	X	GaBi 4.4	ecoinvent 2.2	CML 2001	n/a	n/a	X
(Traverso et al., 2012)	1 m^2 of photovoltaic modules	x	SimaPro	ecoinvent	Eco-indicators 99 2.06	n/a	LCSD	n/a
(Zhou, Jiang, and Qin 2007)	Travel distance of 200 km	n/a	n/a	n/a	n/a	n/a	n/a	n/a

the first-author affiliation), peer-reviewed journals, the type of study, and the addressed energy sub-sector.

The work of Zhou, Jiang, and Qin (2007), which was an energy sector-related study focused on the impact assessment of different options of fuel production, was the first LCSA case study published in the scientific literature and set the pace for future developments. As shown in Fig. 2, the number of publications slowly grew since then, especially after 2011, when UNEP/SETAC published its guidelines for LCSA (Ciroth et al., 2011) and boosted research interest regarding this area. Up until the selection of the analyzed articles (December/2020), 2019 has been the year with most LCSA publications in the aimed field (nine papers), followed by 2020 (seven papers), and the years of 2018 and 2016, which accounted for 4 publications each.

Even though the evolution of publications in the energy area seems small, the few studies that conducted systematic literature reviews in LCSA indicate the energy field as the one that concentrates the larger number of publications. The work of Tarne et al. (2017) ranked the energy sector as the third industrial sector with more publications, followed by fuels (accessed together in this study). Two other recent review articles signal that energy systems grew to be the most studied industry division in LCSA research (Costa et al., 2019; Wulf et al., 2019). Considering these previous works, the findings of this research confirm the progression of energy-related LCSA publications.

Regarding the geographical distribution Table 3, it is possible to notice the publications are concentrated around Europe and Asia. The UK (seven publications) and China (five publications) are the highest-ranking countries, followed by a string of countries with three or fewer publications. An important aspect here is the fact that publication in series is responsible for the higher ranks of these countries, such as the work of Stamford and Azapagic (2014; 2012). All studies published by the UK can be traced to the same research group, accounting for circa 21% of all analyzed publications. These findings point out that even though energy-related LCSA is a growing trend, few countries still contribute to this scientific field (as judged based on the first-author affiliation). Concerning the scientific journals, it can be noticed that the articles have been almost evenly spread along with a variety of energy and sustainability-related journals (4). The

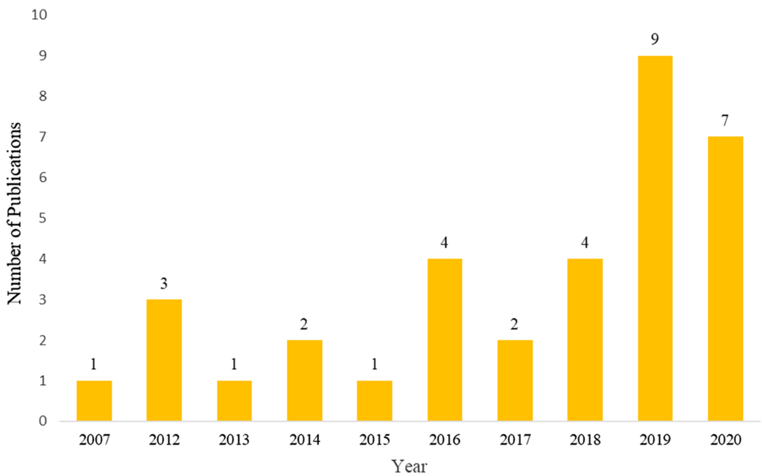

Fig. 2 Number of publications over the years

Table 3 Geographical distribution of publications

Country (first-author)	Number
UK	7
China	5
Italy	3
Spain	3
Australia	2
Germany	2
Portugal	2
Qatar	2
USA	2
Austria	1
Greece	1
Japan	1
Netherlands	1
Pakistan	1
Sweden	1

Journal of Cleaner Production, along with *Sustainability* and *The International Journal of Life Cycle Assessment* published four articles each, featuring together as the main channels of publication in this scientific segment. The remaining articles were published in 14 different journals. These findings evidence how LCSA developed across different scientific niches, contributing to general sustainability discussions, and contributing to sector-specific discussions. Table 4 presents the distribution of analyzed publications per journal.

Table 4 Distribution of publications by journal

Journal name	Publications
Journal of Cleaner Production	4
Sustainability	4
The International Journal of Life Cycle Assessment	4
Applied Energy	3
Sustainable Production and Consumption	3
Computers and Chemical Engineering	2
Energy Policy	2
International Journal of Energy Research	2
International Journal of Hydrogen Energy	2
Chemical Engineering Transactions	1
Energies	1
Energy	1
Energy Conservation and Management	1
Energy for Sustainable Development	1
Fuel	1
Renewable and Sustainable Energy Reviews	1
Sustainable Energy Technologies and Assessments	1

Table 5 Distribution of publications by type of study

Type	Number	%
Case study	17	50.0
Methodological development	7	20.6
Mixed study	9	26.5
Review	1	2.9
Total	34	100%

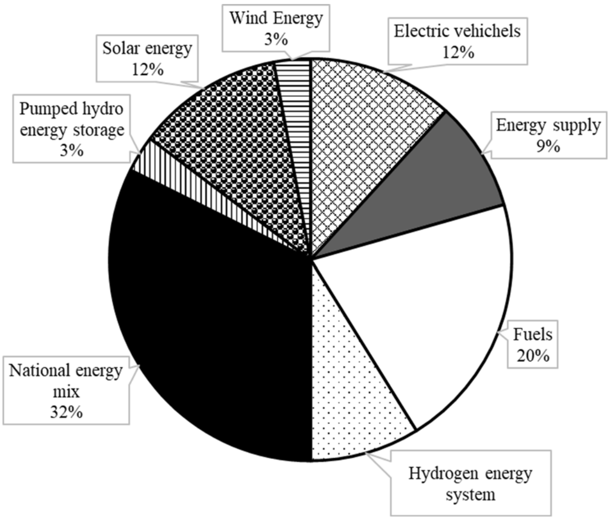

Fig. 3 Distribution of publications by addressed energy sub-sector

Table 5 shows the article classification distribution. A growing trend in case studies publications can be noticed, as 50% of all studies have the goal of presenting a direct LCSA application. However, the combination of case studies with methodological development (mixed studies) is the second-highest ranked type of publication assessed (26.5%), followed closely by papers that aimed solely at presenting methodological and theoretical advancements (20.6%). Even though review articles in the LCSA research are still scarce, one article fitted the systematic review protocol and was incorporated in the review (Collotta et al., 2019). Regarding the relation of analyzed studies to the energy sector, Fig. 3 illustrates the distribution of publications according to the sub-sectors of industrial niches linked to the energy sector. The predominant focus of the publications is directed to sustainability assessment of national energy mixes, or the evaluation of future national electricity generation systems, accounting for eleven studies (32%). By far, this is the subject that generated more interest in the scientific community, as fuels, the second most discussed topic was addressed in seven publications (20%). Solar energy and electric vehicles followed raked together in third place accounting for four publications each (12% each). The remaining 12 publications covered the five sectors encountered in the review, accounting for 23.5% of the total.

Table 6 reflects the distribution of LCSA methodological approaches present in the literature portfolio. The vast majority of studies followed the procedure proposed by Kloepffer (2008) and further disseminated by the UNEP/SETEC guidelines (Ciroth et al., 2011).

Table 6 Distribution of LCSA approaches of the analyzed publications

Approach	Number
LCSA = LCA + LCC + SLCA	25
I-O LCSA	3
Novel methodology	4
LCSAnalysis	1
n/a	1
Total	34

A total of 25 publications, representing circa 75% of all analyzed studies, addressed the total sustainability of energy systems through the separated assessment of the social, economic, and environmental aspects (as described in Eq. 1). Even though some authors used a slightly different nomenclature when presenting their evaluations of sustainability pillars, either by combining two areas, such as "socioeconomic" (Kabayo et al., 2019), or addressing LCC as a "techno-economic" analysis (Li et al., 2018; Stamford and Azapagic 2014; 2012), the studies aimed at the same methodological approach and were clustered together.

The second most applied approach was Input–Output LCSA, applied in three articles. A fourth article that applied this approach was also analyzed, but as these papers were the first to combine Input–Output LCSA with a novel 9-step fuzzy MCDA (Gumus et al., 2016), it was gathered with the other three publications that presented novel methodology pathways. The work of Ren and Toniolo (2018) and Manzardo et al. (2012) shows innovative approaches, both by combining LCSA with a different methodology. The first presents a framework that combines LCSA with an improved version of the decision-making trial and evaluation laboratory (DEMATEL) MCDA method. The second combines LCSA with gray relation analysis (GRA). The last article that presented a novel methodology was the work of Ekener et al. (2018), which extended the assessment of social impacts through values-based weighting methods.

Only one publication used the LCSAnalysis method (Corona & San Miguel, 2019). The environmental dimension was evaluated by combining attribution and consequential LCA; the economic pillar was assessed through LCC and Multi-regional Input–Output; the social aspect was addressed via SLCA and Social Hotspots Analysis (SHA).

Lastly, the work of Collotta et al. (2019) was not grouped with other publications as it shows a review of critical sustainability indicators for biofuels, not a practical use of the LCSA.

4.2 Main life cycle definitions and characteristics

Tools and definitions utilized to conduct the studies are compiled in Table 2. To understand the level of standardization between LSCA studies, the authors analyzed the main mandatory and optional characteristics of life cycle related studies (as described by the ISO standards). Since LCA is the methodological base for LCSA (Finkbeiner et al., 2010), the former shares a lot of the basic processes and core concepts with the latter, such as the obligatory definitions and phases presented in the ISO 14,040 and 14,044 (2006a, 2006b) (objective and scope, system boundary, functional unit, impact categories, etc.), but most importantly, the fact that both assessment methods are built upon the robust theoretical and scientific directives of LCT (Kabayo et al., 2019; Zimek et al., 2019). The first six columns of Table 2 represent some of the obligatory requirements of an LCA study, as stated in the ISO 14,040 (ISOa 2006) (functional unit, system boundary, software, database, LCIA method, allocation method). The last two columns, Aggregation/MCDA, and Sensitivity Analysis are part of the non-mandatory steps described by the same norm.

The results show that no general pattern was found between the publications. Table 2 describes a list of articles that applied a large array of tools and methodological choices. For example, 12 publications (35%) failed to explicitly mention the system boundary set for the analysis, a critical definition in LCT-related studies. The most overlooked requirement was allocation, addressed in only four papers. Only two studies (less than 6%) succeeded in presenting all the ISO requirements. Even though some of the articles do not focus on the practical application of LCSA, but rather focus on methodological development pathways, the number of obligatory requirements overlooked implies the lack of compliance with ISO standards and harmonization between LCSA studies in the energy sector.

A total of eleven publications did not use or failed to mention which database was adopted to obtain secondary data for performing the results. The Swiss *ecoinvent* database was the most applied across the selected publications, appearing in 16 studies. The *Chinese Life Cycle Database* (CLCD), *EXIOBASE*, *Gemis Database*, and *World Input–Output Database* (WIOD) were utilized in only one publication. Only two of 34 studies adopted and shared which database was used for social data collection. Valente et al. (2019) and Corona and San Miguel (2019) employed the database PSILCA database and Social Hotspot Database, respectively.

Various software and LCIA methods were employed to calculate the life cycle impacts of the energy systems studied. SimaPro and GaBi feature the most used software. CML and ReCiPe are the preferred LCIA methods, as shown in Table 2. An expected variety of versions from both software and LCIA methods is noticed in the same table, as they regularly go through updates to better operate and translate the system's impacts.

A sum of 18 analyzed papers (53%) applied either an MCDA method or other aggregation of results, showing a growing trend between LCSA studies. Nine of which took the LCSA approach supported by UNEP/SETEC (Ciroth et al., 2011) presented in Eq. 1. However, the same guidelines instruct against applying MCDA or aggregation methods for result communication, and propose that LCSA results should be delivered according to the three separate dimensions of sustainability. Seven of the 11 papers that applied LCSA to assess the sustainably of national energy systems utilized either MCDA or aggregation methods, accounting for 35.5% of all analyzed papers. The application of such methods in other sub-sectors was also expressive. The reasons for consequences of MCDA and aggregation application in LCSA energy research are further discussed in Sect. 5.

Table 7 shows the application distribution of such methods across the selected papers. Results reveal that the most employed MCDA method was multi-attribute value tree analysis (MAVT), used in six publications. The TOPSIS method ranked second, with three applications. All other MCDA methods were employed by only one study. All articles which applied MCDA chose one specific method, excepting the work of Vogt Gwerder et al., (2019), that applied different methods to determine trade-offs between off-grid home and grid-connected households (MAVT, stochastic multi-criteria acceptability analysis (SMAA), variable interdependent parameter analysis (VIP)).

The aggregation of results in LCA and LCSA through the development of endpoint categories or single scores is a common practice between practitioners to provide more concise and easily understood results (Kalbar et al. 2017; Ren 2018a). The only aggregation method applied more than once was life cycle sustainability dashboard. The other authors

Table 7 MCDA and aggregation methods applied in the selected publications

Method	Number	Reference
MCDA		
DEMATEL	1	(Ren & Toniolo, 2018)
MADA	2	(Onat et al., 2020; Azapagic et al., 2016)
MAVT	6	(Atilgan & Azapagic, 2016; Ekener et al., 2018; Guo et al., 2020; Roinioti & Koroneos, 2019; Santoyo-Castelazo & Azapagic, 2014; Vogt Gwerder et al., 2019)
SMAA	1	(Vogt Gwerder et al., 2019)
TOPSIS	3	(Gumus et al., 2016; Wang et al., 2019; Ren, 2018)
VIKOR	1	(Aberilla et al., 2020)
VIP	1	(Vogt Gwerder et al., 2019)
Aggregation		
Life Cycle Assessment Dashboard	2	(Traverso et al., 2012; Yu & Halog, 2015)
Single score aggregation	1	(Akber et al., 2017)
Summed-ranked analysis	1	(Stamford and Azapagic, 2014)
Sustainability crown	1	(Corona & San Miguel, 2019)

performed result aggregation through the elaboration of single scores, summed-rank analysis, or sustainability crown.

The last characteristic of life cycle studies presented in Table 2 is the use of Sensitivity Analysis, a procedure to estimate what effect in terms of methods and data the choices made in the study had in the final results (ISOb 2006). Forty-one percent of all selected papers performed this non-obligatory step in their work, which accounts for 14 publications. Nine of which were employed in combination with MCDA or aggregation methods, to reinforce the robustness of delivered results. The remaining four articles applied sensitivity analyses to their results without any form of aggregation.

4.3 Sustainability indicators

As previously mentioned, LCSA studies address the three segments of sustainability. However, the impacts regarding each dimension are quantified following different methodologies. LCA determines environmental impacts through impact categories (ISOa 2006). LCC relies on economic indicators (total cost, levelized cost, tax, payback time, and many more) identify, account, and categorize all the costs incurred during a life cycle of a product or a service (Giorgi, Lavagna, e Campioli, 2019; Swarr et al., 2011). SLCA, the most controversial of the three methodologies, presents life cycle impacts concerning a set group of stakeholders (Benoît et al., 2013). The impact categories elected are shown in Table 8. Economic indicators are presented in Table 9. Finally, Table 10 displays the social indicators applied in the selected papers. The indicators featured in Tables 8, 9, 10 are all the indicators found in the list of 34 publications reviewed in this study.

Noteworthy is the approach taken by Kabayo et al. (2019) and Gumus et al. (2016), which combined the social and economic pillars, assessing their impacts under the "socio-economic" dimension of sustainability. For comparative purposes, the indicators described by the authors were analyzed through their relation to the economic and social dimension and divided accordingly between Tables 9 and 10

Table 8 Impact categories applied in the selected publications

Impact Category	Environmental Indicator	Reference
Acidification	Base saturation in natural soils	(Guarino et al., 2020;Jingzheng Ren & Toniolo, 2018; Aberilla et al., 2020; Guo et al., 2020; Kabayo et al., 2019; Roinioti e Koroneos 2019; Valente et al., 2019; Vogt Gwerder et al., 2019; Wang et al., 2019; Li et al., 2018; Ren, 2018; Akber et al., 2017; Atilgan & Azapagic, 2016; Yu & Halog, 2015; Santoyo-Castelazo & Azapagic, 2014; Stamford and Azapagic 2014; Traverso et al., 2012; Cerrato and Miguel 2020)
Aquatic acidification	Base saturation in freshwater/marine water	(Kabayo et al., 2019)
Energy Consumption[a]	Energy used, available, or in surplus	(Onat et al., 2014; Gumus et al., 2016; Hoque et al., 2019; Li, Roskilly, e Wang 2018; Traverso et al., 2012)
Eutrophication[b]	Phosphorus and dissolved inorganic nitrogen concentration in freshwater/marine water	(Guarino et al., 2020; Aberilla et al., 2020; Guo et al., 2020; Kabayo et al., 2019; Roinioti & Koroneos, 2019; Vogt Gwerder et al., 2019; Wang et al., 2019; Li et al., 2018; Atilgan & Azapagic, 2016; Yu & Halog, 2015; Santoyo-Castelazo & Azapagic, 2014; Stamford and Azapagic 2014; 2012; Traverso et al., 2012)
Fossil depletion[c]	Upper heating value	(Hoque et al., 2020; Aberilla et al., 2020; Kabayo et al., 2019; Vogt Gwerder et al., 2019; Wang et al., 2019; Ekener et al., 2018; Atilgan & Azapagic, 2016; Cerrato and Miguel 2020)
Global Warming[d]	Infra-red radiative forcing increase	(Zhou, Jiang, and Qin 2007; Onat et al., 2020; Hoque et al., 2020; Guarino et al., 2020; Onat et al., 2014; Jingzheng Ren & Toniolo, 2018; Gumus et al., 2016; Aberilla et al., 2020; Guo et al., 2020; Corona & San Miguel, 2019; Hoque et al., 2019; Onat et al., 2019; Roinioti & Koroneos, 2019; Ekener et al., 2018; Li, Roskilly, amd Wang 2018; J. Ren, 2018; Akber et al., 2017; Azapagic et al., 2016; Atilgan & Azapagic, 2016; Santoyo-Castelazo & Azapagic, 2014; Stamford and Azapagic 2014; 2012; Traverso et al., 2012; Cerrato and Miguel 2020)
Human toxicity[e]	Risk increase in disease incidence	(Onat et al., 2014; Guo et al., 2020; Kabayo et al., 2019; Atilgan & Azapagic, 2016; Yu & Halog, 2015; Santoyo-Castelazo & Azapagic, 2014; Traverso et al., 2012; Cerrato and Miguel 2020)

Table 8 (continued)

Impact Category	Environmental Indicator	Reference
Land use[f]	Area of agricultural, natural, or urban land occupied or transformed	(Hoque et al., 2020; Onat et al., 2020; Gumus et al., 2016; Aberilla et al., 2020; Guo et al., 2020; Onat et al., 2019; Akber et al., 2017; Ren, 2018; Stamford and Azapagic 2014; 2012)
Material recyclability	Amount of recycled material	(Stamford and Azapagic 2014; 2012)
Metal depletion[g]	Ore grade decrease	(Kabayo et al., 2019; Wang et al., 2019; Atilgan & Azapagic, 2016; Yu & Halog, 2015; Santoyo-Castelazo & Azapagic, 2014)
Ozone depletion	Stratospheric and tropospheric ozone decrease	(Guarino et al., 2020; Aberilla et al., 2020; Roinioti & Koroneos, 2019; Li et al., 2018; Atilgan & Azapagic, 2016; Yu & Halog, 2015; Santoyo-Castelazo & Azapagic, 2014; Stamford and Azapagic 2014; 2012; Traverso et al., 2012)
Particulate matter formation	PM2.5 or PM10 population intake increase	(Onat et al., 2020; Onat et al., 2014, 2019; Aberilla et al., 2020)
Photochemical oxidant formation[h]	Summer smog increase	(Aberilla et al., 2020; Guarino et al., 2020; Onat et al., 2020; Guo et al., 2020; Onat et al., 2019; Wang et al., 2019; Ren, 2018; Akber et al., 2017; Atilgan & Azapagic, 2016; Yu & Halog, 2015; Santoyo-Castelazo & Azapagic, 2014; Stamford and Azapagic 2014; 2012; Cerrato and Miguel 2020)
Terrestrial ecotoxicity	Hazard-weighted concentration increase in natural soils	(Aberilla et al., 2020; Atilgan & Azapagic, 2016; Azapagic et al., 2016; Roinioti & Koroneos, 2019; Santoyo-Castelazo & Azapagic, 2014; Stamford & Azapagic, 2012; Traverso et al., 2012; Yu & Halog, 2015)
Tropospheric ozone precursor potential	Tropospheric ozone decrease	(Roinioti & Koroneos, 2019)
Water depletion[i]	Increase in water consume	(Hoque et al., 2020; Kabayo et al., 2019; Onat et al., 2020; Onat et al., 2014; Gumus et al., 2016; Aberilla et al., 2020; Guo et al., 2020; Corona & San Miguel, 2019; Onat et al., 2019; Ekener et al., 2018)

Table 8 (continued)

Impact Category	Environmental Indicator	Reference
Water ecotoxicity[j]	Hazard-weighted concentration increase in freshwater/marine water	(Aberilla et al., 2020; Kabayo et al., 2019; Vogt Gwerder et al., 2019; Atilgan & Azapagic, 2016; Yu & Halog, 2015; Santoyo-Castelazo & Azapagic, 2014; Stamford and Azapagic 2014; 2012)
Other[k]	Different Environmental Impacts	(Guarino et al., 2020; Onat et al., 2020; Onat et al., 2014, 2019)

[a]Combines Cumulative Energy Demand, Cumulative Exergy Demand, Energy Consumption, Energy Circularity, Energy Surplus and Energy Ratio.

[b]Combines Freshwater Eutrophication, and Marine Eutrophication.

[c]Combines Fossil Depletion and Non-Renewable Fossil Demand.

[d]Combines Global Warming, GWP100, and Climate Change.

[e]Combines Human Toxicity, Human Carcinogenic Toxicity, Human Non-carcinogenic Toxicity and Hazardous Waste Generation

[f]Combines Urban Land Occupation, Agricultural Land Occupation, Natural Land Transformation, Land Footprint, Forestry, Grazing, Cropland and Ecological Footprint.

[g]Combines Metal Depletion, Abiotic Resource, and Abiotic Depletion

[h]Combines Photochemical Smog Formation, Photochemical Zone Formation Potential, and Photochemical Oxidant.

[i]Combines Water depletion, Water Scarcity Footprint, Blue Water Scarcity and Water Stress.

[j]Combines Freshwater and Marine Water Ecotoxicity.

[k]Combines Energy Inputs from Nature, Fishery, and CO2 Uptake Land

Table 9 Economic indicators applied in the selected publications

Economic Indicator	Reference
Air emission cost	(Onat et al., 2014)
Annualized costs[l]	(Aberilla et al., 2020; Akber et al., 2017; Yu & Halog, 2015)
Availability factor	(Li et al., 2018; Stamford and Azapagic 2014)
Business profit[m]	(Onat et al., 2014; Gumus et al., 2016; 2016; Li et al., 2018)
Capacity factor	(Li et al., 2018; Santoyo-Castelazo & Azapagic, 2014)
Capital cost	(Guo et al., 2020; Roinioti & Koroneos, 2019; Ren, 2018; Akber et al., 2017; Atilgan & Azapagic, 2016; Santoyo-Castelazo & Azapagic, 2014; Santoyo-Castelazo & Azapagic, 2014)
Cost balance	(Corona & San Miguel, 2019)
Cost variability	(Stamford & Azapagic, 2012)
Dispatchability	(Santoyo-Castelazo & Azapagic, 2014)
Energy content of a fuel	(Ekener et al., 2018)
Energy cost	(Kabayo et al., 2019; Traverso et al., 2012)
Financial incentive	(Stamford & Azapagic, 2012)
Fuel costs[n]	(Ren, 2018; Akber et al., 2017; Azapagic et al., 2016; Stamford and Azapagic 2014)
Government tax	(Gumus et al., 2016)
Gross Domestic Product (GDP)	(Onat et al., 2014, 2019)
Immediacy	(Stamford & Azapagic, 2012)
Import	(Gumus et al., 2016; Onat et al., 2014; Santoyo-Castelazo & Azapagic, 2014)
Investment Cost	(Vogt Gwerder et al., 2019)
Levelized cost[o]	(Guo et al., 2020; Corona & San Miguel, 2019; Roinioti e Koroneos 2019; Valente et al., 2019; Vogt Gwerder et al., 2019; Li et al., 2018; Akber et al., 2017; Azapagic et al., 2016; Atilgan & Azapagic, 2016; Yu & Halog, 2015; Santoyo-Castelazo & Azapagic, 2014; Stamford and Azapagic 2014; 2012)
Lifetime of global fuel reserves	(Stamford and Azapagic 2014)
Material Costs	(Traverso et al., 2012)
Multiplier effect	(Corona & San Miguel, 2019)
Net present value	(Yu & Halog, 2015)
Operating and maintenance costs[p]	(Jingzheng Ren & Toniolo, 2018; Aberilla et al., 2020; Corona & San Miguel, 2019; Vogt Gwerder et al., 2019; Wang et al., 2019; Ren, 2018; Stamford and Azapagic 2014; 2012; Traverso et al., 2012)
Payback time[q]	(Corona & San Miguel, 2019; Guo et al., 2020; Li et al., 2018; Yu & Halog, 2015)
Recycling cost	(Wang et al., 2019)
Technological lock-in	(Stamford & Azapagic, 2012)
Time to plant start-up from start of construction	(Santoyo-Castelazo & Azapagic, 2014
Total annualized costs	(Atilgan & Azapagic, 2016)
Total cost[r]	(Guarino et al., 2020; Hoque et al., 2020; Onat et al., 2020; Zhou, Jiang, and Qin 2007; Corona & San Miguel, 2019; 2019; Hoque et al., 2019; Onat et al., 2019; Wang et al., 2019; Ekener et al., 2018; Santoyo-Castelazo & Azapagic, 2014)
Transport cost	(Ekener et al., 2018)
Value-added	(Corona & San Miguel, 2019)

Table 9 (continued)

[l]Combines Annual Costs, Annualized Costs, Annualized Capital Costs

[m]Combines Business Profit, Profitability, Income, Operating Surplus and Gross Operating Surplusn Combines Fuel Costs and Fuel Costs Sensitivity

[o]Combines Levelized Cost, Total Levelized Cost, Levelized Cost of Electricity and Levelized Cost of Operation, and Levelized Cost of Storage

[p]Combines Operating and Maintenance Costs, Goods and Services, Production cost, Labor Force, and Operability

[q]Combines Payback Time and Energy Payback Time

[r]Combines LCC and Total Cost

To facilitate understanding and due to the different versions of LCIA methods, software, and nomenclature used by the various authors, similar indicators were clustered under a broader term (i.e., the impact categories Global Warming, GWP100, and climate change were clustered under the Global Warming indicator shown in Table 8).

4.4 Environmental indicators

8shows a variety of impact categories used to assess the impacts of energy systems. The divarication of applied categories was expected, as the choice of which impact categories to use relies solely on the practitioner. However, the attention given to certain categories was more representative than to others. Global Warming is the most applied impact category, followed by Acidification and Eutrophication. In contrast, some categories appear in only one publication (Aquatic Acidification and Tropospheric Ozone Precursor Potential). The environmental assessment through an energy-related impact category, here clustered under energy consumption was appointed in only five studies, even though all selected papers had a strict relation to the energy sector. These results may imply that authors focus on impact related to other environmental compartments, rather than analyzing energy-related indicators such as CED or CExD. It is important to acknowledge that the choice and availability of impact categories are intrinsically dependent on the version of the software and LCIA methods applied. Hence, some categories presented low recurrence or had to be clustered with more often applied categories. Further discussions are presented in Sect. 5.

4.5 Economic indicators

The list of clustered analyzed economic indicators is presented in Table 9. Thirty-one different indicators were applied across the selected papers. LCC indicators followed a different logic in comparison to the environmental dimension, where the majority of categories were chosen for at least two different authors. Table 9 shows that the economic pillar is addressed through several different indicators, many of which are applied in only one publication. The most recurring indicator was levelized cost, followed by operating and maintenance costs, total cost, and capital cost. A total of 19 indicators were applied in only one of the screened publications. Some authors, like Zhou, Jiang, and Qin (2007) and Hoque et al. (2019), preferred to assess the economic dimension without recurring to several indicators, and applied a simple sum of the total costs needed to the production of the studied FU. Nonetheless, authors like Stamford and Azapagic (2014) or Ekener et al. (2018) applied an extensive list of economic indicators in their work. Such divergence and variety

Table 10 Social indicators applied in the selected publications

Social Indicator	Reference
Access to material resources	(Wang et al., 2019)
Availability factor	(Guo et al., 2020)
Awareness and training	(Yu & Halog, 2015)
Bill reduce rate	(Li et al., 2018)
Business ethics	(Yu & Halog, 2015)
Care for employees	(Yu & Halog, 2015)
Child labor	(Valente et al., 2019; Wang et al., 2019);
Commitment to carbon emission reduction	(Yu & Halog, 2015)
Community engagement	(Yu & Halog, 2015)
Company social performance	(Corona & San Miguel, 2019)
Compatibility and stability	(Yu & Halog, 2015)
Compensation	(Onat et al., 2019)
Consistency with federal government	(Yu & Halog, 2015)
Contribution to peak and the dependence on fossil energy	(Guo et al., 2020)
Contribution to research collaboration	(Yu & Halog, 2015)
Contribution to society	(Wang et al., 2019; Yu & Halog, 2015)
Contributionto technology development	(Wang et al., 2019; Yu & Halog, 2015)
Disabled workers	(Traverso et al., 2012)
Employment[s]	(Hoque et al., 2020; Onat et al., 2014; Gumus et al., 2016; Aberilla et al., 2020; Guo et al., 2020; Corona & San Miguel, 2019; Hoque et al., 2019; Onat et al., 2019; Roinioti & Koroneos, 2019; Vogt Gwerder et al., 2019; Kabayo et al., 2019; Li et al., 2018; Ren, 2018; Akber et al., 2017; Azapagic et al., 2016; Atilgan & Azapagic, 2016; Yu & Halog, 2015; Stamford and Azapagic 2014; 2012; Traverso et al., 2012; Cerrato and Miguel 2020)
End of life management	(Yu & Halog, 2015)
Energy efficiencyand security[t]	(Zhou, Jiang, and Qin 2007; Jingzheng Ren & Toniolo, 2018; Aberilla et al., 2020; Kabayo et al., 2019; Roinioti & Koroneos, 2019; Atilgan & Azapagic, 2016; Akber et al., 2017; Stamford and Azapagic 2014);
Feedback mechanism	(Wang et al., 2019; Yu & Halog, 2015)
Forced labor	(Wang et al., 2019)
Freedom of association and collective bargaining	(Wang et al., 2019)
Gender gap[u]	(Traverso et al., 2012; Valente et al., 2019)
Health and safety[v]	(Guarino et al., 2020; Hoque et al., 2020; Onat et al., 2020; Onat et al., 2014; Aberilla et al., 2020; Hoque et al., 2019; Roinioti & Koroneos, 2019; Valente et al., 2019; Vogt Gwerder et al., 2019; Wang et al., 2019; Ren, 2018; Atilgan & Azapagic, 2016; Yu & Halog, 2015; Santoyo-Castelazo & Azapagic, 2014; Stamford e Azapagic 2014; 2012)
Human rights and corruption;	(Stamford & Azapagic, 2012)
Large accident risk;	(Stamford & Azapagic, 2012)

Table 10 (continued)

Social Indicator	Reference
Local community impacts (staff from local community)	(Stamford & Azapagic, 2012)
Local suppliers and investment in local community	(Stamford & Azapagic, 2012)
Maturity	(Ren & Toniolo, 2018)
Nuclear proliferation	(Stamford & Azapagic, 2012)
Policy	(Wang et al., 2019)
Potential ofCPHES and UPHES	(Guo et al., 2020)
Profitability	(Yu & Halog, 2015)
Social acceptability	(Aberilla et al., 2020; Hoque et al., 2019; Ren & Toniolo, 2018; Santoyo-Castelazo & Azapagic, 2014)
Social influences	(Yu & Halog, 2015)
Socialrisks[w]	(Corona & San Miguel, 2019; Ekener et al., 2018)
Subsidy	(Wang et al., 2019)
Supplierrelationship	(Yu & Halog, 2015)
Supply diversity and fuel storage capability	(Stamford & Azapagic, 2012)
Taxation[x]	(Gumus et al., 2016; Onat et al., 2014, 2019)
Transparency	(Yu & Halog, 2015)
Useof abiotic resources[y]	(Hoque et al., 2020; Zhou, Jiang, and Qin 2007; Azapagic et al., 2016; Santoyo-Castelazo & Azapagic, 2014; Stamford and Azapagic 2014; 2012)
Use of local resources	(Aberilla et al., 2020)
Volumeof liquid CO2 to be stored	(Santoyo-Castelazo & Azapagic, 2014)
Volume of radioactive waste to be stored	(Stamford and Azapagic 2014)
Wage[z]	(Wang et al., 2019; Traverso et al., 2012);
Workers benefits	(Traverso et al., 2012)
Working hours	(Traverso et al., 2012)

[s]Combines Employment, Indirect Employment, Direct Employment, Employment (Direct and Indirect), Employment provision, Local Employment Net Employment Generated, Job Creation, and Total Employment

[t]Combines Diversity in Fuel Supply Mix, Energy availability, Energy Efficiency, Energy Security, Exergy Efficiency, Imported Fossil Fuel Potentially Avoided, and Security of Supply

[u]Combines Employment by Gender, Average Wage per Gender, Equal Opportunities

[v]Combines Carcinogenic Toxicity, Injuries, Fatalities due to large accidents, Non-carcinogenic Toxicity, Health and safety, Health expenditure, Human Health, Safety, Severe Accidents Fatalities, Total Health Impacts from Radiation, and Worker Injuries

[w]Combines Social Risk, and Weighted social risks

[x]Combines Government Tax and Total Tax

[y]Combines Intergenerational Equity (Abiotic Resources and Storage of Radioactive Waste, Use of Abiotic Resources (elements and fossil fuels), and Use of Non enriched Uranium in a Reacton

[z]Combines Working Minimum Wage, Salary, and Fair Salary

are linked to fact that LCC, except for a practical guideline proposed by Swarr et al. (2011), has no standard regulating its procedures.

4.6 Social indicators

Social impact assessment recurred to even more indicators than the economic dimension. Table 10 presents a list of 50 different indicators. Similar to the previously discussed results regarding the economic pillar, the majority of social indicators listed were applied in only one publication. The most employed indicator was the evaluation of direct and indirect employment regarding the studied product system, which featured in 21 articles, followed by energy efficiency and security and health and safety. Thirty-four of the listed indicators (approximately 70% of the total) were applied only in one study. The work of Stamford and Azapagic (2014), Yu and Halog (2015), and Zhou, Li, and Wei (2019) were the ones that presented the most extensive list of social indicators. Conversely, Cerrato and Miguel (2020) and Li et al. (2018) recurred to no more than two indicators. Similar to the economic dimension, the lack of standardization in SLCA contributes to the widely different choice for addressed stakeholders and assessed indicators.

Findings also show that some authors recurred to LCA impact categories to assess the social impacts of the studied system. Impact categories like human toxicity (carcinogenic and non-carcinogenic) were often applied to address health and safety issues across different studies (Onat et al., 2014; Aberilla et al., 2020; Onat et al., 2019; Vogt Gwerder et al., 2019; J. Ren, 2018; Stamford and Azapagic 2014; 2012). Furthermore, the indicator use of abiotic resources was assessed through metal depletion and related categories in several studies (Zhou, Jiang, and Qin 2007; Azapagic, 2016; Santoyo-Castelazo & Azapagic, 2014; Stamford and Azapagic 2014; 2012).

The relation between indicators across sustainability dimensions in LCSA studies along with other related aspects is further discussed in Sect. 5.

5 Discussions

Even though LCSA seems to be still in its development phase, not fully reaching the proposed status of "The Future of LCA" (Guinée et al., 2011; Zimek et al., 2019), its use has spread at a rapid pace amid the practitioners the last decade (Costa et al., 2019; Wulf et al., 2019). However, due to its state of development, professionals and specialists face several constraints in the search for trustworthy and comparable results, critical when addressing system-wide changes required by sustainable development (Savaget et al., 2019). On the one hand, there are main challenges regarding LCSA methodology and implementation, such as the different degrees of maturity between assessment methods. On the other hand, some difficulties can be addressed with a focus on a specific sector, for example, the inconsistencies that hinder the comparability and cohesion of energy sector-related studies, such as the variety of metrics, indicators, another criteria applied to similar systems. Key issues concerning LCSA application in the energy field are discussed below.

5.1 Diversity of life cycle features in LCSA studies

The review suggests none of the publications present methodological and operational choices similar to another. These results corroborate with the findings of Collotta et al.

(2019), which encountered no general pattern while discussing LCSA indicators for biofuels. Owing to the absence of standardization of LCC, SLCA, and LCSA itself, practitioners interested in assessing the sustainability of energy sector-related systems (among other sectors) might find rather broad specifications. Results shown in Sect. 4 indicate how differently publications approached their goal and scope, even if in similar cases. Such diversity shows that scientific publication is trying to explore different and better ways to assess the sustainability of systems through LCSA. Nevertheless, the variety of aspects and definitions make the comparability between studies and systems virtually impossible. Although differences between LCSA studies are recurring and even expected, from a policy-making perspective capable of contributing to sustainable development and battling energy scarcity, a standardized LCSA approach provides great advantages for the interpretation of projects, especially in a multi-faceted environment such as the energy sector.

System boundaries of energy-related LCSA applications

The integrative and interdisciplinary nature of the studied sector brings a challenge to LCSA practitioners. Due to the integrated nature of the energy sector, all selected papers in this study show systems that are deeply connected with other industrial sectors. Examples are the work of Onat et al. (2016), which are directed to the sustainability performance electric car value chains, and therefore linked to both automotive industry and electricity generation and consumption sectors; or even the many studies directed to the evaluation of impacts of national energy mixes. Even though a completely separated sector sounds unrealistic in the modern world, the relation of all addressed system boundaries with other processes and stakeholders proves to be still difficult from an LCSA perspective, essentially thanks to the system boundaries that each assessment method applies. The system boundaries set for different sustainability dimensions are not always identified as they may disclose different aspects of the studied system, reflecting on the use of a variety of indicators and definitions.

Our results imply that the recurrent inconsistency in system boundaries choice is rooted in the assessment of the economic and social segments through the life cycle approach. As argued by Costa et al., 2019), practitioners tend to apply a life cycle rationale only in the evaluation of environmental impacts, while dealing with the social and economic dimensions mainly for the foreground system. Although that issue is true for some of the selected papers (Ekener et al., 2018; Azapagic et al., 2016; Cerrato and Miguel, 2020), the opposite is true for the majority, as many authors applied indicators relating to the background system that exceeds the analyzed system boundary, i.e., the indicators GDP, global fuel reserves (for more examples, please refer to Table 9).

A clear definition of system boundaries in LCSA studies is even more urgent in energy-related studies, as more than one-third of selected publications failed to explicitly mention the boundaries set in the study (please refer to Sect. 4.3). Furthermore, the choice for consistent system boundaries is critical for the election of FU and indicators assessed. As both the LCC and SCLA lack proper standards, without well-defined system boundaries authors may apply an excess of indicators, which ultimately translates into communication issues due to a large amount of data, or may choose just a couple of indicators, causing the oversimplification for results (which does not translate the broad concept of the system's *sustainability*). The consistent choice of system boundaries seems to be a critical step on the path of LCSA toward its methodological refinement, one that influences the totality of the studies and results, and therefore cannot be overlooked.

5.2 Sustainability indicators in LSCA of energy systems

Regarding sustainability indicators applied in the selected papers, results suggest that the publications converge to the same main environmental impacts (Table 8), with a concentration in the assessments of Global Warming, Acidification, Eutrophication, and other pressing impacts related to the specific system in focus. However, when it comes to the economic and social dimensions, there is a large diversity of applied indicators.

This discussion goes back to the absence of standardization in LCSA. Since there are no more than simple guidelines for assessing these sustainability dimensions, authors vary their attention given to such pillars to broaden their analyses and find connections to impacts across different levels of society. For example, Corona and San Miguel (2019) only assessed the social pillar through the assessment of jobs generated (the most recurring indicator). Then again, Yu and Halog (2015) used more than 15 different indicators to access social sustainability in their work (Table 10). As the same logic extends to the economic dimension, it can be concluded that more attention should be paid to the choice of indicators in energy-related LCSA applications. Figure 3 shows that all publications address technologies deemed important for SDG 7 related issues. Therefore, rather than assessing innumerous and pulverized indicators, authors should focus on impacts and indicators that could support the decision- and policy-making processes, contributing to a clearer communication of LCSA results.

The review findings also show a crossing of indicators between dimensions. The human toxicity impact category was often applied to SLCA to access health and safety issues. That is also true for the metal depletion category (or abiotic depletion, depending on software/LCIA method). Profitability was also mentioned in one of the studies as a social indicator, even though it has a clear economic nature. Although the use of impact categories and indicators across sustainability dimensions may be feasible (given proper justification), authors should be careful with indicator selections and application across sustainability dimensions to avoid double counting and provide better comprehensiveness to the communicated results.

5.3 Integration of results in energy-related LCSA

Another pressing issue is the integration of results in energy-related LCSA studies. The majority of analyzed publications applied specific methods to facilitate the understanding of results, especially MCDA (please refer to Sect. 4.3). MCDA is an already renowned methodology in LCA studies, commonly used to identify and comprehend possible trade-offs (Zanghelini, Cherubini, and Soares, 2018). However, to give equal attention and exposition to each dimension, the UNEP/SETAC guidelines propose the communication of LCSA results according to each pillar of the TBL (Ciroth et al., 2011). Our results show that practitioners are taking the opposite path, as the number of publications that feature such methodology in LCSA-related studies increased over the years.

The high recurrence of MCDA and aggregation methods reflects the needs and characteristics of the energy sector. First, LCSA studies of energy systems often deal with large amounts of data, commonly reaching nation or community-wide scales (Aberilla et al., 2020; Akber et al., 2017; Li et al., 2018; Valente et al., 2019). The authors argue that methods to compile and deliver results in a clearer way are welcome on such occasions, as they simplify the communication and decision-making process.

A second reason regards policy-making. Some of the analyzed results present specific sections directed to describe guidelines and influence policy-making (Aberilla et al., 2020; Akber et al., 2017; Atilgan & Azapagic, 2016; Santoyo-Castelazo & Azapagic, 2014; Stamford and Azapagic, 2014). The findings aimed at policy implications are commonly delivered based on different scenarios assessed through these methods. Best practices and recommendations are then drawn according to integrated results to guide decision makers to the most sustainable scenario. Thus, the use of such methodologies in the alignment of LCSA studies in the analyzed papers has proven to counter the UNEP/SETAC methodological sheets (Ciroth et al., 2011) proposal and help practitioners deliver far-reaching results.

Based on the aforementioned issues, the authors argue that further implementation of MCDA methodologies alongside LSCA studies is beneficial to the overall outcome and should be pursued by practitioners. Some of the advantages from the simultaneous implementation of such techniques are: (1) It raises the methodological robustness of the analyses; (2) avoids confusions and bias in the selection of results between the plethora of indicators that LCSA studies commonly present (for more information, please refer indicators shown in Tables 8, 9, 10); and (3), when applied to provide result aggregation, aids in the communication of results and a better understanding of the outcomes of the study by the decision makers. The main limitation that arises from this approach is the fact that it is time-consuming and depends on the high expertise of the practitioner.

5.4 LCSA approaches and combination with other methodologies

Different LCSA approaches feature in the analyzed papers (Table 6). Irrespective of which methodological path, all assessed methods delivered conclusive results regarding the sustainability of the appointed energy system. Although all approaches show sound methodological structures and analyses, the one suggested by Kloepffer (2008) seems to be the preferred one between practitioners, as it is the most widely applied between all case studies analyzed. This approach is also the simplest one between all here analyzed, like LCA, LCC, and SLCA, and applied separately (Costa et al., 2019). Hence, for communication and comparison purposes, this review makes the case for further application of this specific LCSA approach in the energy field, as it proves to be well disseminated by the research community and capable of addressing the three elements of TBL thoroughly.

Furthermore, different studies combined LCSA with other assessment methods not based on LCT. Methods like GRA and SHA were applied to either deepen the assessment in a sustainability dimension or deliver further arguments regarding the addressed system. Due to the current development status of LCSA, the integration with other methods may contribute to fill gaps in the current methodological structure (i.e., issues related to LCC or SLCA), or better understand a specific problem. Indeed, as pointed out by several authors, LCSA's interdisciplinary outline provides a clear platform for the integration of models (Guinée, 2016; Onat et al., 2019; Zimek et al., 2019). Therefore, the strength of LCSA lies in its ability to integrate various methods within its framework (i.e., MDCA). As long as life cycle definitions and methodologies are meticulously followed, other methods may help the development of novel approaches and contribute to the operationalization and scientific dissemination of LCSA.

6 Conclusion

This study performed a literature review on the present state of development and application of LCSA in the industrial sector with the highest recurrence in the topic, the energy sector. Based on the 34 papers that respected the outlined methodology, the authors sought to provide methodological approaches, definitions, and indicators used to evaluate the sustainability of the energy system. The analyzed portfolio presented papers spread throughout several subsections of the energy sector, more specifically, all activities involved in the fuel exploitation, storage, production, transportation, and distribution of energy. The assessment of the national energy mixes was the most recurring addressed topic and offers a good example of how holistic but yet assertive LCSA studies are. Overall, the majority of articles dealt with renewable options or energy scarcity-related topics, showing the potential of LCSA to be applied to determine better options and strategies regarding SDG 7.

Different LCSA approaches were identified in energy-related studies. The most recurring one is exemplified in Eq. 1. Even though this is a very straightforward procedure, different methodological issues arise from it. Since SLCA commonly deals with qualitative indicators, and LCC may even display non-tangible activities, simply summing up such results may lead to inconsistencies in the impact assessment procedure. Moreover, often LCC and SLCA system boundaries do not respect the same boundaries set for LCA, contributing to divergences regarding which aspects are considered in the studied system. The definition of system boundaries proves to be a critical issue across the selected papers. Either due to the abovementioned issue or because of unclear communication of the appointed system boundaries in the studies. Such obstacles rank high among the most pressing issues related to LCSA methodological refinement and were identified in many of the analyzed publications.

The review stresses the lack of pattern regarding LCT characteristics and approaches between the analyzed studies. Indeed, even though the LCSA literature related to energy systems is not abundant, a variety of operationalization definitions was identified. Although differences between LCSA studies are recurring and even expected, the lack of standardizing across studies may hinder the development of the method toward its proposed goal—aiding in decision-making and policy-making processes. This paper argues that although SCLA and LCC do not have specific standards such as LCA, practitioners should push toward more coherent and comparable studies to help decision and policy makers. Findings also point that such an argument is even more compelling in the energy field due to its transactional and integrative characteristics.

An interesting trend found reinforces the policy-making-related applicability of energy-related LCSA—the integration of results through the application of MCDA or aggregation methods. This approach seeks to facilitate the understanding and communication of results by delivering sustainability results clearly and unambiguously. As the majority of selected publications approached their results in this way, the authors infer that this is a beneficial trend to the sustainability evaluation of the energy field. Following this approach, one can compile frequent large amounts of data in energy systems, and ultimately deliver results that could influence policy-making toward more sustainable practices effectively.

Based on the performed review, the results of this study corroborate with other authors (Costa et al., 2019; Wulf et al., 2019; Zimek et al., 2019) by stating that the most pressing issue related to the LCSA application lies in its harmonization. Clear delimitation of system boundaries, impact categories, social and economic indicators, in addition to the possibility of integration with other methods, would contribute toward more robust LCSA assessments. Additionally, due to its critical importance to sustainable development, and a large amount of data existent, the energy sector sets the perfect platform for the application of comprehensive and comparable methodologies such as LCSA. Future studies could focus on further integration between MCDA and LCSA, create solutions for the interactions between system boundaries across sustainability dimensions, and develop energy-related case studies to increase the discussion and insights that could assist in sustainable energy production, renewable energy expansion, and tackling energy scarcity.

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Code availability The authors declare that there is no code relevant to the study.

Data availability The authors declare that all data related to this research are presented in the Supplementary Material file annexed to the article.

Declarations

Conflict of interest The authors have no conflicts of interest to declare that are relevant to the content of this article.

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