Journal of Environmental Management 264 (2020) 110464

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: http://www.elsevier.com/locate/jenvman

Review

Sustainability assessment of energy production: A critical review of methods, measures and issues

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ARTICLE INFO

Keywords:
Sustainability
Energy production
Systematic review
Systems thinking
Energy policy
Sustainability assessment

ABSTRACT

Sustainable operations of energy production systems have become an increasingly important policy agenda globally because of the massive pressure placed on energy resources needed to support economic development and population growth. Due to the increasing research interest in examining the operational impacts of energy production systems on the society and the environment, this paper critically reviews the academic literature on the clean, affordable and secure supply of energy focussing on methods of assessments, measures of sustainability and emerging issues in the literature. While there have been some surveys on the sustainability of energy production systems they have either tended to focus on one assessment approach or one type of energy generation technology. This study builds on previous studies by providing a broader and comprehensive examination of the literature across generation technologies and assessment methods. A systematic review of 128 scholarly articles covering a 20-year period, ending 2018, and gathered from ProQuest, Scopus, and manual search is conducted. Synthesis and critical evaluation of the reviewed papers highlight a number of research gaps that exist within the sustainable energy production systems research domain. In addition, using mapping and cluster analyses, the paper visually highlights the network of dominant research issues, which emerged from the review.

1. Introduction

Over the past three decades, Sustainable Development has become a mainstream concept, which has underpinned key international and national policy initiatives on environmental and socio-economic development. It is based on this concept that grand sustainability agenda such as the Millennium Development Goals (MDGs) were implemented at the turn of the century followed by the subsequent adoption of the Sustainable Development Goals (SDGs) in 2015. These have been motivated by concerns over climate change and global population growth leading to focus on the development of holistic approaches to tackle sustainability challenges and ensure a more sustainable future (Reinhardt et al., 2019). The sustainability of energy production systems has become central to these grand sustainability challenges and so trickled down to the national levels.

Indeed, the seventh goal of the SDGs aims at ensuring access to affordable, reliable, sustainable and modern energy for all (United Nations, 2015). Sustainability is a major energy policy requirement because the limits of conventional energy generation sources have become clearer for policy-makers. Additionally, the indirect impacts and new risks associated with even renewable generation resources have made planning decisions on the operations of energy production systems pertaining to sustainability even more challenging. This global requirement for clean, secure and affordable energy, the awareness of the limits of non-renewable primary resources, environmental and social impacts of both renewable and non-renewable energy generation technologies have been promoted by strong research in the area, which has subsequently engaged policy, industry and public interest.

Policy relevance of sustainability in energy systems is not only evident in the SDGs, but by energy policy objectives and legally binding treaties in various intergovernmental organizations (Stamford and Azapagic, 2014). The United Kingdom, for example, has set three priority areas in its energy review: reduction in greenhouse gas emissions, secure energy supply for the future, and reduction in fuel poverty (Allan et al., 2015). Similarly, to confront rising energy demands, the 2015 UN Climate Change Conference in Paris agreed to the reduction in greenhouse gas emissions with the aim of limiting global warming below 2 °C by 2100 (Olmedo-Torre et al., 2018). The Economic Community of West African States (ECOWAS) has also passed an ECOWAS Energy Efficiency Policy (EEEP) and a Renewable Energy Policy (EREP) with aim of

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https://doi.org/10.1016/j.jenvman.2020.110464
Received 28 October 2019; Received in revised form 12 January 2020; Accepted 18 March 2020
Available online 4 April 2020

ensuring universal access to clean electricity by 2030 (Ohene-Asare and Turkson, 2018). These are a few of the several global and national efforts at ensuring sustainable practices in energy generation.

In this study, we conduct a synthesis and critical review of research on the sustainable operation of energy production systems by examining the main and emerging issues, the measures of sustainability and the methods employed in examining sustainability. The growing interest in this area of research has attracted a number of surveys on various issues related to sustainability and energy generation to be specific, even ignoring the plethora of survey papers on sustainability in general (Diaz-Balteiro et al., 2017; Brandenburg et al., 2014). While these studies have provided useful insights into the literature on sustainability assessment of energy generation systems they have either tended to focus on one assessment approach (Varun et al., 2009; Asdrubali et al., 2015) or one type of energy generation technology (Peng et al., 2013; Liu, 2014). As a result, there is a limited understanding of the extent of the literature focussing on the sustainability of the operations of energy systems in general. Additionally, studies that have been broader in focus have not yet provided insights on emerging issues like systems modelling and the concepts of weak and strong sustainability as they relate to energy systems. Such studies are shown in Table 1.

Varun et al. (2009), for example, reviewed the literature on life cycle assessment (LCA) of renewable electricity generation systems. Their aim was to point out that such renewable energy generations systems also produce carbon emissions when examined throughout the product's life (that is, cradle to grave). Peng et al. (2013) also conducted a review of literature on LCA, however, they focused on LCA literature on solar photovoltaic (PV) systems. By examining the literature on energy payment and greenhouse gas (GhG) emissions of five common PV systems, they concluded that PV technologies have been proven to be very sustainable and environmentally friendly. They also postulated that the sustainability of PV systems will only improve with improvement in manufacturing technologies. The strength of the LCA approach is its ability to assume a systems approach and quantify all impacts of the entire supply chain thereby allowing for rational choice among energy supply systems (Varun et al., 2009).

Similar to Varun et al. (2009) and Peng et al. (2013), in relatively recent times, Asdrubali et al. (2015) and Martín-Gamboa et al. (2017) have based their reviews on LCA approaches to sustainability. Except that while Asdrubali et al. (2015) aimed at harmonizing the LCA results of papers in literature, Martín-Gamboa et al. (2017) were interested in reviewing studies that had combined LCA and Data Envelopment Analysis (DEA) for sustainability assessment of energy systems. After extensive harmonization and normalization of empirical results presented in the literature, Asdrubali et al. (2015) found that while wind-powered technologies are at the low end of environmental impact, geothermal and PV technologies are at the high end of environmental impact compared to other renewable energy generation technologies. On their part, Martín-Gamboa et al. (2017), after reviewing the literature on potentials for the combining of LCA and DEA modelling approaches, proposed a new methodological framework that allows for endogenous integration of life-cycle indicators, ranking and benchmarking and energy planning and facilitations of decision-making process using dynamic DEA approach. Note that the study by Martín-Gamboa et al. (2017) did not only focus on renewable energy generation sources as was done in the previous reviews discussed.

Table 1
Surveys on sustainable energy systems.

Authors	Title
Varun et al. (2009)	LCA of renewable energy for electricity generation systems—A review
Bazmi and Zahedi (2011)	Sustainable energy systems: Role of optimization modelling techniques in power generation and supply—A review
Peng et al. (2013)	Review on life cycle assessment of energy payback and greenhouse gas emission of solar photovoltaic systems
Liu (2014)	Development of a general sustainability indicator for renewable energy systems: A review
Asdrubali et al. (2015)	Life cycle assessment of electricity production from renewable energies: Review and results harmonization
Martín-Gamboa et al. (2017)	A review of life-cycle approaches coupled with data envelopment analysis within multi-criteria decision analysis for sustainability assessment of energy systems

There have been other reviews and surveys, which are not focussed on LCA or its combination with other modelling techniques. Bazmi and Zahedi (2011), for example, conducted a review on the role of optimization modelling techniques in sustainable power generation and its supply. They find that optimization approaches have found wide applications especially at the decision making and planning stages such as production planning, scheduling, location, resource allocation, engineering design and even transportation problems. They see potential intellectual advances if superstructure-based modelling and optimization is widely adopted in such studies. The study was based on a systems approach where alternative technologies are captured (Bazmi and Zahedi, 2011). Finally, the review by Liu (2014) was focussed on developing a general sustainability indicator that includes many basic sustainability indicators. Their proposed framework, which incorporates multicriteria decision making (MCDM) approaches, provides a numerical basis, even for fuzzy criteria, which they believe is useful as a guide for sustainability assessment of various renewable energy systems.

In this study, we examine 128 peer-reviewed journal articles that examine the social, economic and environmental impacts of various energy production systems. We provide insights on the extent of research in the area in terms of methods used, measures and emerging research issues discussed. Based on which we identify gaps and provide recommendations for setting a research agenda. The next section provides a brief overview of the concept of sustainability, systems thinking and other research themes reviewed in this study. This is followed by Section 3 which presents the survey methodology used in gathering the papers for the review. Section 4 is a critical evaluation of the selected literature and the identification and presentation of gaps and recommendations. Finally, Section 5 provides conclusion which lays the future research agenda.

2. Literature review

2.1. Sustainability: towards a definition

While the origin of the term 'sustainability' can be traced to sixteenth-century German foresters (Kuhlman and Farrington, 2010; Schlör et al., 2012), modern resurgence of the term is attributed to the 1987 report of the Brundtland Commission of the United Nations World Commission on Environment and Development - WCED (Bonevac, 2010; Kajikawa et al., 2007). The report stresses that: "sustainability requires views of human needs and well-being that incorporate such non-economic variables as education and health enjoyed for their own sake, clean air and water, and the protection of natural beauty" (Brundtland, 1987, p. 53). This stimulus for sustainability is strengthened by the realization that human-activities are jeopardizing its own long term interests through atmospheric changes, biodiversity and freshwater depletion, among others (McMichael et al., 2003). As such, fundamental to the area of sustainability and sustainable development is the idea that human and natural systems interact and are interconnected (Schoolman et al., 2012).

Although the term 'sustainability' is ubiquitous in policy and literature, there is little consensus on its meaning. It is a difficult concept to define because it is an evolving one and its meaning is both abstract (Martens, 2006) and contextual (Kajikawa et al., 2007; Young and Dhanda, 2013) and described in varying ways by different parties (Campbell and Garmestani, 2012). Post the 1987 Brundtland report; definitions in literature have had some human or ecological underpinnings. Shaker (2015) sees sustainability as humanity's target goal for human and ecosystem equilibrium. Finkbeiner et al. (2010) observe that sustainability should not focus on environmental impact alone but there should be a balance or even an optimum in environmental, economic and social well-being dimensions of society. Similarly, McMichael et al. (2003) believe that sustainability means transforming human ways of living in order to maximise chances that environmental and social conditions can support human security, well-being and health indefinitely. Kahle and Gurel-Atay (2013), p. 9 believe that "sustainability implies the use of resources in a manner that can continue indefinitely."

The problem becomes confounded when the meaning of sustainable development is explored. Critics believe 'sustainable development' is vague and can be an oxymoron (Bonevac, 2010; Kajikawa et al., 2007). Additionally, Bonevac (2010) and Büyüközkan and Karabulut (2018) do not make a distinction between sustainability and sustainable development. For Giovannoni and Fabietti (2013) they use the terms sustainability and sustainable development as analogues though observing that whereas sustainability refers to a 'state', sustainable development refers to the processes required to be at that state. However, Gallopín (2003) asserts that the two concepts are quite different in that the word "development" points to the idea of a progressive change, which may not necessarily be quantitative. Shaker (2015) sees sustainable development as the holistic approach and temporal processes that lead us to the end-point of sustainability. Perhaps, the most widely cited definition of sustainable development is the one outlined in the Brundtland report that sustainable development is, "*development that meets the needs of the present without compromising the ability of future generations to meet their own needs*" (Brundtland, 1987, p. 43).

There remains no unanimity regarding theoretical and conceptual foundations on the issues of sustainability and sustainable development (Shaker, 2015). Despite its vagueness and ambiguity, the Brundtland report's definition has been highly instrumental and spurred up research interest with respect to the future of the planet (Mebratu, 1998). It is even believed that the absence of a rigorous definition of the terms provides an opportunity for more debate about the issues in search of common grounds (Lélé, 1991). However, modern discussions on both sustainability and sustainable development believe that life on earth has environmental limits for which humans, through interconnected consideration of the economy, environment and society, have a responsibility of preserving (Young and Dhanda, 2013). These environmental limits are highlighted in the concept of the planetary boundaries (Rockström et al., 2009).

2.2. Systems thinking and sustainability

There are complex relationships within and between the various systems that need to be integrated into any sustainability assessment. There is a need to understand the dynamic behaviour of the system under study in order to develop a more integrated and resilient solution to sustainability objectives (Fiksel, 2006). There is also little unanimity and theoretical grounding on sustainability (Shaker, 2015), which makes sound and robust assessment for policy difficult. Gallopín (2003) advocates that due to the ambiguity and lack of strong theoretical background to the field, sustainability could be discussed from a system's perspective where careful consideration of the aspect of the system to be sustained should be emphasised.

Systems thinking can offer a useful perspective, compared to other analytical approaches, when thinking about sustainability since it is a way of thinking in terms of connectedness, relationships and contexts, which are key underlining principles of sustainability (Gallopín, 2003). This provides a more robust and conceptually sound framework for sustainability analysis. Indeed, the idea of the system view of sustainability is gradually becoming mainstream in sustainability literature. A survey of 96 papers, published from 1990 to 2015, on systems thinking in sustainability analysis by Williams et al. (2017) found that 67 out of the 96 papers published using systems thinking were published from 2010. This shows a growing acceptance of the ability of systems thinking in enhancing understanding of the dynamic interactions within and across interconnected systems (Whiteman et al., 2013; Williams et al., 2017). System's thinking of sustainability is very useful given the complexity, dynamic interactions and nonlinear interdependencies of related systems (Fiksel, 2006).

Since all physically existent systems are open, the behaviour of a system depends on the system's internal interactions, how the external elements or variables from the environment affects it and outputs of the system into the environment (Gallopín, 2003). There is, therefore, the need to always determine the boundaries of the system under study and the adjacent systems that interact with the system under study (Foley et al., 2003). Fig. 1 shows possible interactions between energy generation system, ecology and society. The systems approach can be useful as the basis for understanding the meaning of sustainability by providing insight into the need for continuous management of system resources over time; understanding the significance of interactions among systems; understanding the importance of planning and designing the system; appreciating the need to re-evaluate the system sustainability at regular intervals and examining issues related to resilience of the system (Fiksel, 2006; Foley et al., 2003). It is therefore useful to examine in this survey the extent to which system thinking has been used in sustainability assessment literature of energy generation.

2.3. Dimensions of sustainability

The core ideas of modern thinking around sustainability and sustainable development are based on the interaction and inter-dependency between different dimensions of a system. This is because industrial, social and ecological systems are closely linked when making effective decisions regarding sustainability (Fiksel, 2006; Finkbeiner et al., 2010). Since the Brundtland report, there have been two major developments in sustainability literature (Kuhlman and Farrington, 2010): a) the three dimensions of sustainability and; b) the distinction between 'strong' and 'weak' sustainability. The three dimensions assessment of sustainability pioneered by Elkington (1997) is a framework which emphasises the need to consider economic, social and environmental objectives in sustainability assessment. Although there have been arguments to include other dimensions like technological and institutional dimensions to sustainability (International Atomic Energy Agency, 2005, Maxim, 2014), the three dimensions remain the basis of most sustainability assessment. The three dimensions consist "environment", "economy" and "social well-being", for which society (or the system under consideration) needs to find a balance (Finkbeiner et al., 2010). The distinction

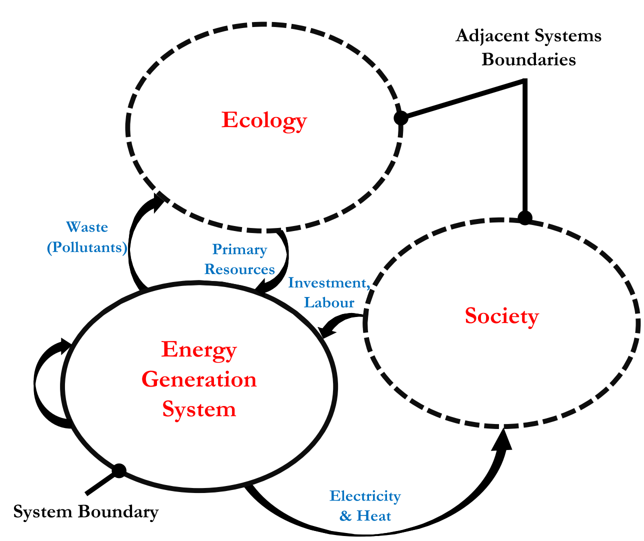

Fig. 1. A system representation of the relationship between energy generation system, ecology and society (Adapted from Foley et al. (2003)).

between 'strong' and 'weak' sustainability coined by Pearce and Atkinson (1992) and further divided by Turner (1993), presents different perspectives on the relationship between nature and society. Based on economic growth theory, the concept of capital is defined to comprise manufactured capital, human capital and natural capital (Pearce and Atkinson, 1998). Weak sustainability ensures that aggregate capital is non-declining, even to the detriment of other types of capital over time, therefore, implicitly allows for substitution of capital for all forms of capital. Strong sustainability (very strong by Turner (1993)), on the other hand, advocates that the next generation should inherit a stock of environmental assets which is not less than the stock inherited by the current generation (Kuhlman and Farrington, 2010), therefore, imposes an additional constraint on weak sustainability, as proponents of this school believe that natural capital has no substitute.

Although these dimensions of sustainability have served as the building blocs for subsequent developments in sustainability assessments, it is uncertain the extent to which sustainability assessment literature in energy systems rely on such conceptual perspectives. It is important to review whether other sustainability dimensions, other than the three, are prominent in the literature as well as the extent to which models and methods employed for sustainability assessment incorporate the ideas of strong and weak sustainability. It is important to examine the preferences/weights given in the literature to the various dimensions when making a composite judgement of the sustainability of the system.

2.4. Energy and sustainable development

Activities related to the sustainable development of energy systems include a reduction in emissions and pollutant gases, increased safety of energy supply, use of renewable energy sources, improved energy efficiency and improved quality of life (Jovanović et al., 2009). Energy, therefore, has implications on the environment, economic development and social welfare. Ensuring that affordable and reliable energy is derived from environmentally appropriate supply sources is critical for sustainable development (Afgan et al., 2007b). This is because of the substantial environmental impacts from the production of various forms of energy. Apart from its contribution to social and economic development, energy consumption is recognised as also a major source of greenhouse gas emissions (Lu et al., 2016). A significant proportion of world carbon dioxide (CO_2) emissions and air pollution is as a result of fossil fuel combustion in order to satisfy energy demand (Rafaj et al., 2006). Coal, for example, has the highest CO_2 emissions per kW h but continues to dominate the market due to low cost and high availability (Varun et al., 2009; Evans et al., 2009). The role of energy sustainability is indispensable in social development. This is because the availability of energy is the driving force that facilitates the development of vital social systems such as education, health and employment among others. Principles such as good quality of life, human well-being, equitable opportunities for all, diversity and even democratic civil society are central constituents that form the backbone of a socially sustainable society (Khan, 2015). As development in any society is directly linked with the level of energy consumption, energy is a critical input for national economic development (Mondal and Denich, 2010). It is one of the major pillars of economic development for countries globally (Shaaban and Scheffran, 2017). Electricity demand is a major component of both economic and social development as countries that lack an adequate supply of electric energy find it difficult to ensure positive development in production, national income, health and education (Onat and Bayar, 2010). Access to cheap energy is essential for economic development and poverty reduction, on the other hand, expansion of energy-related infrastructure is critical for energy security (Fouquet, 2016). The dependency on critical and recyclable materials in the production of low carbon energy technologies has become paramount as development of societies and technologies continue to require more and more resources (Jin et al., 2016).

3. Review methodology

We conduct a systematic review in providing a synthesis and critical evaluation of the emerging issues, measures of sustainability and methods used in sustainability research of energy generation systems. This involved a three-stage procedure comprising literature generation, screening and evaluation.

The first stage of the review methodology is the literature generation stage. This is undertaken to gather the papers to be examined in the review process. A broad range of literature on the sustainability of energy generation systems was gathered from ProQuest-Business Premium Collection and Scopus using relevant keywords. For both databases, articles selected were restricted to peer-reviewed scholarly journals published before October 2018 and written in the English language. Additionally, a keyword search was limited to abstract search as highlighted in the Literature Review procedure in Fig. 2. To be considered, an article is expected to have the words 'sustainability' and either 'measurement' or 'assessment' appearing in its abstract together with either 'energy' or 'electricity' generation. This generated a total of 375 articles in ProQuest and 330 in Scopus. It must be noted that since the search was limited to peer-reviewed scholarly articles, reports such as the IPCC (2018) Global warming of 1.5 °C and the Global energy assessment by Johansson et al. (2012), and other non-academic sources which conduct sustainability assessment of energy systems are not included in this review. Such reports usually rely on a plethora of academic sources or later result in peer-reviewed academic papers which are the focus of this survey.

Stage two of the Literature Review process involved screening the papers gathered to identify the relevant literature to be included in the review. The first step in this stage was a title search, where articles were screened for relevance based on the title. Since the work was limited to sustainable operations in energy generation systems, papers that focused on energy use in buildings, public transportation systems and oil and gas extraction etc., were eliminated. If the title was not informative enough to determine acceptance of the paper, a further abstract evaluation was used as the criteria for elimination. Correcting for duplicates in the two databases, a total of 128 articles qualified for the evaluation stage. This final list of 128 articles also included those gathered in a manual search on google scholar, Mendeley recommendations and publisher recommendations, to gather other relevant papers not captured in the database search. These studies are summarised in the supplementary materials section. The final stage of the review process is the evaluation of the articles gathered, which is captured in section 4 of this paper.

4. Results and discussions

4.1. Descriptive analysis

Peer-reviewed articles published on sustainable energy generation are first analysed based on the yearly distribution of publication, publication sources and authors. This provides a broad overview of the articles considered relevant for the survey. Starting with the yearly distribution of papers, it is clear that there is a growing research interest in this area as over 90 per cent of the articles reviewed were published after 2006. Additionally, as of October 2018, 14 articles had already been published equalling the second highest yearly number of publications and only one behind the highest number of 15 articles recorded in 2015 (see supplementary data). This shows the increasing relevance of sustainability to the evaluation of energy generation.

The distribution of the articles based on the publication sources shows that among the sources with a high number of publications in this area are Energy Policy (22), Renewable and Sustainable Energy Reviews (16) and Energy (16). These high impact journals have been leaders in promoting research on the sustainability of energy generation systems. Other high impact journals among the top 15 are Applied Energy (7.9), Environmental Science and Technology (6.653) and Energy Conversion

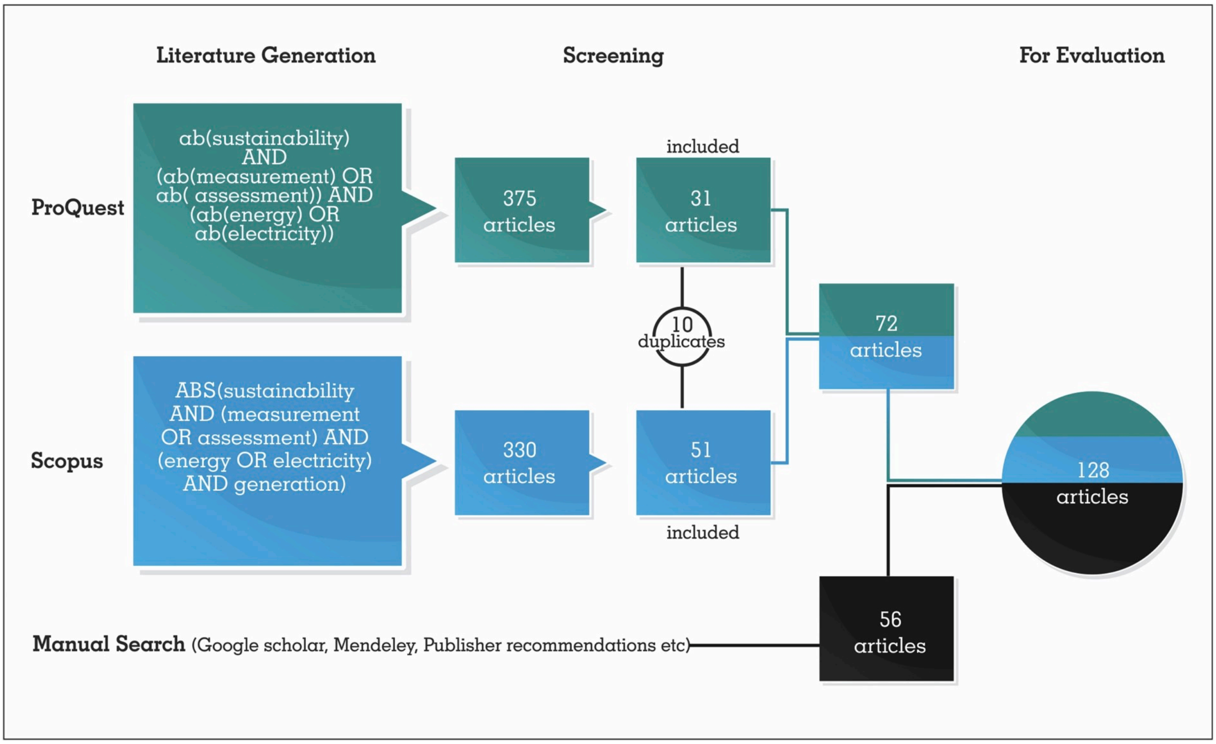

Fig. 2. Literature review procedure.

and Management (6.377). In addition to the 15 sources identified in Figure A2 in the supplementary data, the remaining articles came from 35 other journals within a wide array of academic disciplines.

Table 2 shows the major authors who have contributed to this area. Table 2 is populated based on the frequency of publications rather than the number of citations or H-index. Among the leading authors are Naim H. Afgan, who has contributed to about 12 papers mainly focused on model development, evaluation and scenario analysis on various types of energy sources. These researches have been in collaboration with Maria G. Carvalho, Petros A. Pilavachi, Marina Jovanović and a number of other researchers who also appear in Table 2. Another prominent author is Adisa Azapagic who, together with Laurence Stamford and other researchers, have contributed to the multi-dimensional evaluation of electricity technologies.

4.2. Network analysis

The 128 articles selected for review were subjected to mapping and cluster analyses using VOSviewer (version 1.6.9), a software for analysing and visualizing bibliometric networks, by van Eck and Waltman (2018). Specifically, titles and abstracts of the articles were subjected to co-occurrence analysis in order to identify the most occurring issues in these papers as well as how they link to each other. The strength of the links between the co-occurring terms is measured by the number of times the specific terms occur together in different articles. Additionally, clustering of the terms has been conducted to identify the broader domains in which these terms occur. As such, this mapping and cluster analysis are aimed at identifying the main research issues in the sustainable energy production research domain and how these topics relate to each other (Waltman et al., 2010). The network visualization of the papers is presented in Fig. 3 showing the binary count of terms with at least five occurrences. Additionally, Fig. 3 shows the top 350 strongest

Table 2
Prominent authors on sustainability assessment of energy systems.

No	Author	Count	Cited by[a]	No	Author	Count	Cited by
1.	Naim H. Afgan	12	888	17.	Christian Bauer	2	70
2.	Maria G. Carvalho	7	635	18.	Geoffrey P. Hammond	2	62
3.	Adisa Azapagic	6	307	19.	Craig I. Jones	2	62
4.	Marina Jovanović	4	106	20.	Vukman Bakic	2	52
5.	Laurence Stamford	4	97	21.	Ángel Galán-Martín	2	46
6.	Gonzalo Guillén-Gosálbeza	3	52	22.	L. Jiménez	2	32
7.	Annette Evans	2	563	23.	A. Ewertowska	2	32
8.	Tim J. Evans	2	563	24.	Ibrahim Dincer	2	30
9.	Vladimir Strezov	2	563	25.	Kevork Hacatoglu	2	30
10.	Petros A.Pilavachi	2	212	26.	Marc A. Rosen	2	30
11.	Roland Clift	2	156	27.	Mustafa Music	2	20
12.	Dalia Štreimikienė	2	141	28.	Elma Redzic	2	20
13.	John J. Burkhardt, III	2	119	29.	Anes Kazagic	2	20
14.	Craig S. Turchi	2	119	30.	Jürgen Scheffran	2	8
15.	Garvin A. Heath	2	119	31.	Mostafa Shaaban	2	8
16.	Stefan Hirschberg	2	70	32.	Kathrin Volkart	2	5

[a] *Citations from Scopus as at February 2019.*

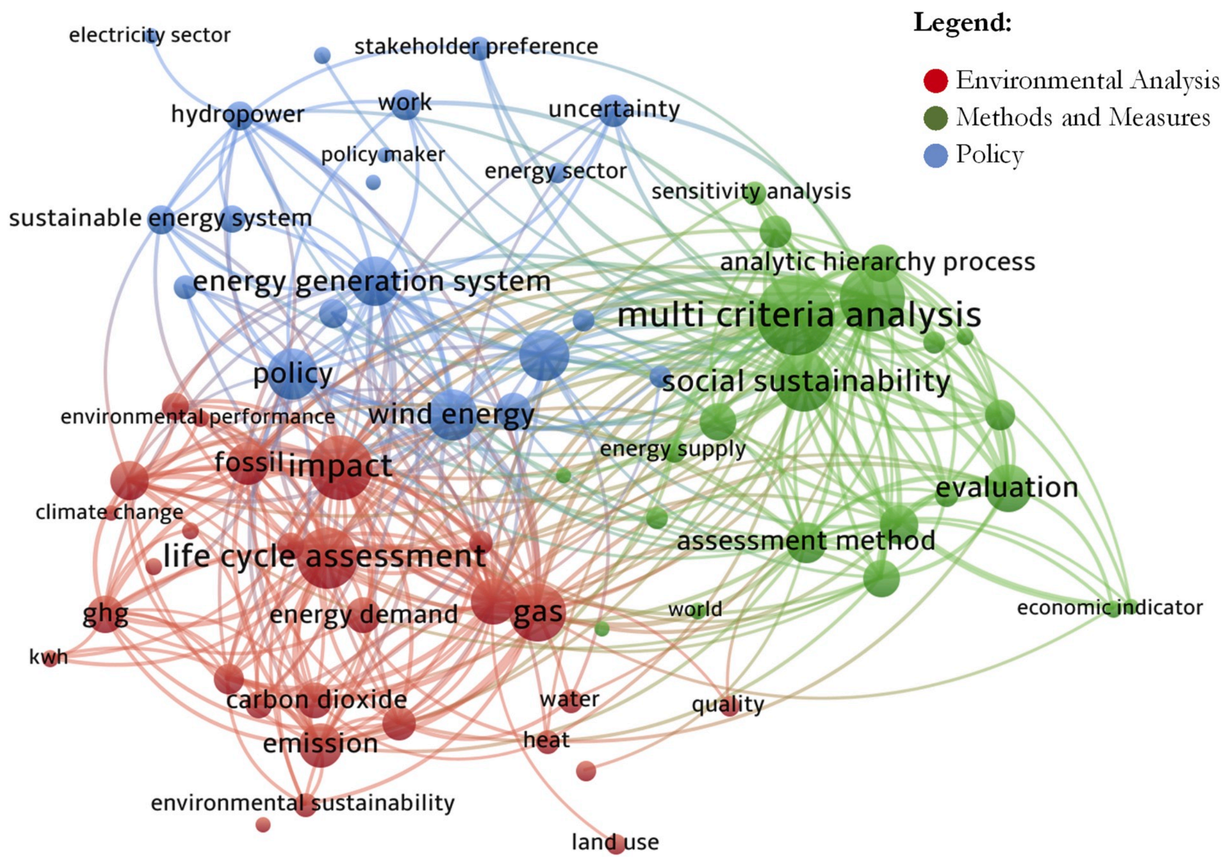

Fig. 3. Network visualization of the most occurring terms in the studies. Size of the bubble reflects the number of occurrences of the term. Links between the terms is measured by the number of times the specific terms occur together in different articles.

links among the terms.

Among the frequently occurring terms in these studies are multi-criteria analysis, impact, life cycle assessment, policy and social sustainability. Multi-criteria analysis, or similar terms such as MCA and MCDM, appeared in 44 different articles and co-occurred with 64 out of the 70 terms that qualified. This is not particularly surprising since the idea of sustainability often requires considering multiple dimensions using multiple indicators. Impact, policy and social sustainability were also among the most frequently appearing terms showing the relevance of impact assessment, that consider social impacts of energy generation, for policy. Note that the size of the nodes in Fig. 3 is based on the number of occurrences of each term in the 128 papers surveyed.

Another important feature of Fig. 3 is the clustering of the terms based on the strength of the association between terms determined by co-occurrences (Waltman et al., 2010). Evidently, the co-occurring terms can be clustered into three main groups. The characteristics of these clusters have been summarised in Table 3.

Cluster one comprises 28 terms appearing, on average, in 13 papers. This cluster is dominated by various non-renewable sources of energy and aspects concerning environmental impacts such as greenhouse gas emissions, carbon and other emissions. Life cycle assessment; one of the main topics, is primarily used for environmental impact assessments of individual products/technologies. It must be noted, however, that the use of LCA, although predominantly used for environmental assessment, has also been used for social impact assessment. Hondo and Moriizumi (2017), for example, conducted a life cycle environmental and socio-economic impact analysis of the employment creation potential of renewable power sources using input-output models. Cluster two comprising 22 items occurring in 14 articles, on average, bother on methods for evaluation. MCDMs, AHP, sensitivity analysis are all approaches for evaluating the sustainability of energy systems. The final cluster mainly captures policy-related issues like renewable energy sources, energy security and uncertainty. This cluster also bothers on the social aspects of sustainability such as stakeholder preference, energy source and technology selection and ensuring secure supply of energy. Research issues captured in these studies, therefore, focus on environmental impact, assessment approaches and energy policy.

4.3. Review of methods of assessment

This section reviews the nature of assessment approaches used in examining the sustainability of the energy generation systems. The study of sustainability issues often requires the integration of multiple dimensions of operation involving multiple indicators (Diaz-Balteiro et al., 2017). The result is the reliance on composite indices to study and quantify the level of sustainability of units under investigation. Methods used for sustainability assessment in these studies include MCDM approaches (Afgan and Darwish, 2011; Doukas et al., 2010), exergy analysis (Koroneos and Nanaki, 2007; Lo Prete et al., 2012), LCA (Evans et al., 2009; Burkhardt et al., 2011; Rehl et al., 2012), and other optimization-based approaches such as multi-objective optimization and tax/subsidy optimization (Zhang et al., 2012; Mondal and Denich, 2010; Resnier et al., 2007). There have been other studies which have been descriptive without the need to form composite indices (Gallego Carrera and Mack, 2010; Tsoutsos et al., 2005).

The most widely used approach for sustainability assessment is MCDM approaches. This is mainly due to the multi-dimensionality of the problem of sustainability which requires that different objectives or indicators are considered or integrated simultaneously (Brandenburg et al., 2014). Indeed Janeiro and Patel (2015) believe sustainability is inherently an MCDM problem. The review of the literature shows the use of a vast variety of MCDM approaches such as a) distance functions like

Table 3
Clustering of literature.

Cluster		Number of Terms	Main topics	Average Occurrences	Average Links
1:	Environmental Analysis	28	impact; life cycle assessment; gas; coal; emission; fossil; environmental impact; ghg; carbon dioxide; energy demand; solar energy; oil; electricity generation	13	46
2:	Methods	22	multi-criteria analysis; criterium; social sustainability; evaluation; assessment method; environment; analytic hierarchy process; comparison; sensitivity analysis	14	42
3:	Policy	20	energy source; policy; wind energy; energy generation system; energy technology; uncertainty; energy security; hydropower; sustainable energy system; energy policy	12	41

TOPSIS (Štreimikienė et al., 2012; Brand and Missaoui, 2014), b) outranking approaches like PROMETHEE (Troldborg et al., 2014; Buchholz et al., 2009) and NAIADE (Browne et al., 2010; Giampietro et al., 2006), c) hierarchical techniques like AHP (Chatzimouratidis and Pilavachi, 2009; Karger and Hennings, 2009), and ANP (Zhao and Li, 2015), d) ranking and classification methods like DEA (Ewertowska et al., 2016; Galán-Martín et al., 2016) and e) optimizing averages approaches such as MAUT/MAVT (Santoyo-Castelazo and Azapagic, 2014; Phdungsilp, 2010), ASPID (Vučićević et al., 2014) and weighted average (Klein and Whalley, 2015; Frangopoulos and Keramioti, 2010). Approaches have been classified according to Diaz-Balteiro et al. (2017).

These approaches are sometimes used in combination with other approaches with crisp and fuzzy indicators. In their assessment of the sustainability of urban energy systems in Serbia, Jovanović et al. (2010), for example, used fuzzy set theory together with ASPID approach. The problem with MCDM approaches is usually with the dimension weighting, which may rely on different expert opinions or equal weighting across dimensions. Additionally, the additive nature of most approaches means that poor performance on one dimension can be compensated by higher performance on the other dimensions, which seem to be at variance with the idea of sustainability. These approaches tend to be compensatory and must be interpreted in terms of the trade-off between the dimensions (Hacatoglu et al., 2015a).

The other well-used approach is the LCA method. This is an analytical approach, which allows for the examination of organizational impact across the supply chain. Rehl et al. (2012) used attributional (aLCA) and consequential (cLCA) approaches to analyse biogas system environmental impacts in the German electricity mix. They observed that the calculated environmental performance is affected by the methodology selected. A number of other studies have also used the LCA to estimate 'cradle-to-grave' impact of energy systems. LCA approach is often used together with other MCDM or other aggregating approaches. Roldán et al. (2014), von Doderer and Kleynhans (2014) and Hacatoglu et al. (2015b) all used LCA results together with other MCDM techniques in order to arrive at a composite sustainability index. The review of the papers showed that studies that used LCA tended to mainly focus on the environmental dimension of the operation with little, or no, emphasis on the economic and social aspects of the sustainability triad. It must be noted, however that, the use of LCA goes beyond the environmental dimension. For example, while Hondo and Moriizumi (2017) conducted a life-cycle employment creation potential impact using input-output models, Malik et al. (2016) conducted a triple bottom line LCA of Australian cellulose-refining industry. Also, there are significant variations in the nature of system boundaries examined in the various papers. For example, a number of papers have focussed on a 'cradle-to-gate' thinking (Hammond et al., 2013; Quek et al., 2018) while others conducted a 'cradle-to-grave' assessment (Azapagic et al., 2016; Volkart et al., 2018).

Exergy analysis is another method observed in the review. Exergy analysis includes the quality of the output in the modelling process thereby following the first and second laws of thermodynamics (Koroneos and Nanaki, 2007). The differences in the quality of output are important when comparing different energy conversion processes (Lo Prete et al., 2012). Outside these major approaches, there have been other optimization and descriptive-based approaches used to understand the sustainable operation of energy generation systems. Studies that use descriptive statistics, such as Gallego Carrera and Mack (2010) and Tsoutsos et al. (2005), do not make attempts at generating composite indices but primarily focus on discussing the sustainability of these generating technologies across a number of indicators.

While 'hard' quantitative examination of sustainability is relevant, the importance of stakeholder perceptions and inputs cannot be ignored. This is particularly important since there is a lack of 'soft' approaches like soft systems methodology (SSM), strategic options development and analysis (SODA) among others in the literature reviewed.

4.4. *Review of measures of sustainability*

4.4.1. *Dimensions of sustainability*

Next basis for discussion is the dimensions of sustainability considered by these papers. Generally, in the sustainability literature, the Triple Bottom Line concept first put forward by Elkington (1997), which requires consideration for social, economic and environmental objectives, is well accepted as the holistic dimensions of sustainability. This has therefore been translated into the sustainability literature of energy generation systems. It is important to note that almost every paper made an attempt to examine the impact of the system under investigation based on some clear dimensions. Even the few studies, like Browne et al. (2010), who did not identify specific dimensions being studied, had consideration for environmental, economic or social implications based on the indicators used.

Another observation from the literature is the prevalence of studies, which consider a fourth dimension. Pilavachi et al. (2006), Chatzimouratidis and Pilavachi (2009), Frangopoulos and Keramioti (2010), Rovere et al. (2010), Afgan and Darwish (2011) and Duan et al. (2011) all included a "technical" or "technological" dimension as part of the economic, social and environmental dimensions studied. This fourth dimension is often defined to consider the factors that relate directly to the operation of the generation technology that cannot be considered environmental, social or economic. Maxim (2014) defines it to include the ability to respond to demand, efficiency and capacity factor. The separation of the technical aspect is central to the idea of the systems approach to technology sustainability assessment of Musango and Brent (2011), which integrates the ideas of technology development, sustainable development and systems dynamics. From a systems perspective, the separation or decoupling of the technical dimension from the other dimensions allows for the modelling of the impact of other systems on the technology dimension and vice versa.

4.4.2. Weighting of dimensions

Multi-criteria analysis is by definition an assessment of multiple dimensions of a problem which might have different levels of importance. Weighting is therefore important in any multi-criteria analysis. Dimension and indicator weighting has been one of the critical issues in the sustainability literature. This is mirrored in the energy generation sustainability literature as well. Different papers have different approaches to dimension weighting. These include equal weighting (Evans et al., 2009; Varun et al., 2009), unequal weighting (Doukas et al., 2010; Jovanović et al., 2009) or even both (Klein and Whalley, 2015; Malkawi et al., 2017). There are studies which do not even attempt to weight the dimensions in their assessment. These studies which do not weight dimensions either tend to focus on one specific dimension or provide a descriptive assessment of the sustainable operation of the energy generation systems. As there is no consensus on the importance of the various dimensions of sustainability, studies tend to be subjective in their weighting of dimensions. Most studies, however, conduct some form of scenario or sensitivity analysis to determine the robustness of their ranking to changes in dimension weighting (Lipošćak et al., 2006; Rafaj et al., 2006; Atilgan and Azapagic, 2016).

On how the weights are determined, a number of papers have relied on some form of expert or stakeholder opinions (Dombi et al., 2014, Gallego Carrera and Mack, 2010; Grafakos and Flamos, 2017), using approaches like AHP to determine the overall weight of the dimensions, or have relied on estimation techniques that determine the dimension weights without the need for some direct weight input (Ewertowska et al., 2016, 2017; Galán-Martín et al., 2016). Bojesen et al. (2015) determined the criteria weights from surveys carried out among a group of expert planners and decision-makers from the Danish central government. Cucchiella and D'Adamo (2015) conducted a survey of twelve experts with extensive experience in energy decision making. These experts included senior managers, policymakers and researchers. Similarly, Luthra et al. (2015) considered the opinions of ten experts including project managers, academicians, environment and forest ministry representatives and statistics and programme implementation persons who handle climate change programmes. Others rely on a broader array of stakeholders in order to ensure more representative and broadly acceptable weights. For example, Gallego Carrera and Mack (2010) in their sustainability assessment using social indicators sent surveys to 52 different European stakeholders in the energy sector, such as industry associations, political and administrative institutions, environmental groups, energy consumers and trade unions. Similarly, Parnphumeesup and Kerr (2011) examined stakeholder preferences in their study. They found that preference weights by experts and local residents are statistically different in the Thailand case raising the possibility of a disconnect between policymakers' views and that of other stakeholders. Evaluation approaches like DEA allow the units under investigation to choose their most favourable weights that maximise their performance, hence requiring no need to specify dimension weights (Yang et al., 2014). Others have tended to use weights based on researcher view on the perspective being studied. Moreira et al. (2015), for example, assigned 60% of the weight to the environmental dimension with an 'ecocentric' view.

4.5. Review of emerging issues

4.5.1. Modelling weak and strong sustainability

The idea of capital substitution, which is captured in the debate between weak and strong sustainability (Gallopín, 2003; Turner, 1993) is another modelling dimension that is considered important in this review. Whereas the arguments for a weak form of sustainability support the idea of non-declining aggregate capital even at the expense of individual components of aggregate capital (Pearce and Atkinson, 1998), arguments for the strong form of sustainability do not support the idea of capital substitution or compensation between the various forms of capital (Kuhlman and Farrington, 2010). Capital (K) is defined to comprise manufactured capital (K_m), skills and knowledge of humans, otherwise called human capital (K_h) and natural resources and stock of environmental assets together known as natural capital (K_n) (Pearce and Atkinson, 1998). Mathematically, the difference between weak and strong sustainability can be expressed as (Pearce and Atkinson, 1998):

$$\frac{dK}{dt} \geq 0, \quad \text{where} \quad K = K_m + K_h + K_n \tag{1}$$

$$\frac{dK}{dt} \geq 0, \quad \frac{dK_m}{dt} \geq 0\,, \quad \frac{dK_h}{dt} \geq 0 \quad \text{and} \quad \frac{dK_n}{dt} \geq 0 \tag{2}$$

In other words, the change in aggregate capital K as a result of a change in time t should not fall. However, whereas weak sustainability, as depicted in equation (1) implicitly allows for substitution of capital for all forms of capital, strong sustainability in equation (2) does not allow such substitution.

Papers surveyed were examined on whether they explicitly assumed or conducted their analysis from the perspective of strong or weak sustainability in relation to the relationship between the various forms of capital. Indeed, only, Rogner (2010), Duan et al. (2011), Myllyviita et al. (2013) and Moreira et al. (2015) explicitly indicated the capital substitution assumption made in their modelling. Myllyviita et al. (2013), for example, states that, because compensation between the dimensions of sustainability is allowed in their study, their framework should be considered to support the concept of weak sustainability. Most studies are silent on the issue of factor substitutability although the nature of their modelling seems to suggest weak sustainability. Evidently, there is little consideration for the arguments of strong sustainability in the literature. The study by Giampietro et al. (2006) was one of the few exceptions since their modelling of the post-normal science paradigm in sustainability did not allow for compensation between social and technical dimensions. Closely related to this is the issue of compensability of the dimensions. If the method allows poor performance on one dimension to be compensated by excellent performance on other dimensions, then it can be argued that the dimensions are compensable which is akin to the idea of weak sustainability. This is because the approach allows for trade-off in the various dimensions (Hacatoglu et al., 2015a) and hence the aggregate performance is being maximized even at the expense of individual dimensions. If the approach does not allow for trade-off, however, then it is akin to strong sustainability.

4.5.2. Systems thinking

Another issue considered as a basis for this review is the evaluation of the extent to which the literature includes systems thinking in the sustainability assessment of energy generation systems. Most studies do not consider sustainability as a systems problem. They, therefore, treat the environmental and social systems, for example, as 'black boxes'. There are a few studies that considered some form of the systems approach in the modelling. However, a look at these papers, like Rehl et al. (2012), Roldán et al. (2014) and von Doderer and Kleynhans (2014), that incorporate some systems thinking in the assessment reveal that these are mainly LCA-based papers. LCA is a systemic analytical model (Acquaye et al., 2011; Brandenburg et al., 2014) which requires an assessment of the impact across the life-cycle of the unit under investigation. Azapagic et al. (2016), for example, conducted an LCA assessment of UK's energy sector from extraction of primary resources, through construction, operation, decommissioning, waste treatment and disposal phases of the life cycle. There is little evidence of systems thinking outside the LCA literature especially in the energy generation sustainability assessment literature gathered.

4.5.3. Other research issues

These papers reviewed have studied a broad range of energy generation technologies, from renewables alone (Tsoutsos et al., 2005; Varun et al., 2009), non-renewable sources alone (Frangopoulos and Keramioti, 2010) to a combination of renewable and non-renewable sources (Ewertowska et al., 2016; Shmelev and van den Bergh, 2016). It is important, especially at the national-level energy planning to conduct an assessment that combines both renewable and non-renewable sources in order to understand the social, environmental and economic impacts of various technologies. Some papers even treat the energy sector as a 'black box' and consider sustainability issues from the total energy generated rather than at the technology level (Koroneos and Nanaki, 2007; Giampietro et al., 2006).

At the contextual level, though these studies span a broad range of countries, including both developed and developing nations, it is evident that such sustainability assessment is primarily done at the single state level. Most papers surveyed considered energy generation sustainability in a single country (Lipošćak et al., 2006; Assefa and Frostell, 2007). For example, while Assefa and Frostell (2007) developed an approach for assessing indicators for the social sustainability of technical systems in Sweden, Resnier et al. (2007), Buchholz et al. (2009) and Karger and Hennings (2009) examined various issues in China, Uganda and Germany respectively. Very few studies consider such sustainability issues at the multi-state level or the regional level (Begić and Afgan, 2007; Gallego Carrera and Mack, 2010). However, regional or global assessment is particularly important since energy and sustainability policies are now being formulated at the intergovernmental level rather than the state level. The European Union (EU), for example, has region-level energy policies and directives that are supposed to ensure sustainability in energy generation of member states. The EU, for example, has clear country-specific targets for climate and energy in its renewable energy directives (EEA, 2017). Additionally, the Paris Agreement and the incorporation of sustainable energy as Goal Seven of the SDGs show why energy and environment is a global rather than a national problem.

4.6. Gaps in the literature

From the literature reviewed, a number of research gaps can be identified. Firstly, researches tend to mainly focus on quantitative methods that provide some form of composite indices to study the level and nature of sustainability of units under investigation. There is a lack of studies relying on problem structuring approaches such as 'soft' operations research approaches like soft systems methodology, strategic options development and analysis (SODA) and other qualitative approaches. This is important because such soft approaches are effective in highlighting stakeholder views which are equally important for energy policy formulation and evaluation.

Second, despite the availability of mathematical models and computational techniques for handling multi-objective and multiple indicator problems (Marler and Arora, 2004; Greenberg et al., 2012), current models used for sustainability problems of energy systems do not seem to effectively model the practical implications of the integration of the various dimensions. This is because additive relations between dimensions seen in most MCDM approaches imply compensability, which means poor performance on the environment can be compensated on high economic and social performance or vice versa. This is not consistent with the central idea of sustainability that all three dimensions are important and there is the need to ensure good performance on all dimensions as required in the Triple Bottom Line principles (Elkington, 1997).

Third, although systems thinking to sustainability assessment offers a useful perspective for modelling the interconnectedness, relationships and interactions, which are key underlining principles of sustainability (Gallopín, 2003), systems thinking to sustainability assessment seem to be relegated to mainly life cycle assessment of environmental impact. This is particularly surprising since the systems idea of sustainability is gradually becoming mainstream in sustainability literature (Williams et al., 2017). For instance, there is little evidence of systems thinking outside the LCA literature in the energy sector. This is a clear research limitation given that the energy systems are central to national and regional development and so encompasses economic, social and ecological development (Musango and Brent, 2011). The implication is that the holistic impact of the energy system on environment, economy and society may not be well understood. Systems thinking also allow for the examination of the dynamic interactions and long term effects. There is the need for dynamic sustainability assessment as most methods used support static analysis.

Fourth, while different schools of thought with respect to capital substitution exist in sustainability literature, most studies are silent on this. As such, there is a need for the development of models that can better assess systems based on these sustainability perspectives. Most research papers surveyed are silent on this and implicitly assume weak sustainability. This means that relying on such models assumes an anthropocentric perspective that has the tendency of relegating nature as the source for raw materials and sink for wastes from human consumption (Gallopín, 2003). It is important to study sustainability from the various perspectives in order to better understand and make technical and policy decisions from a more encompassing view of sustainability.

Fifth, as there is no consensus on the importance of the various dimensions of sustainability, studies tend to be subjective in their weighting of dimensions. Irrespective of the approach selected in developing weights, there is the need for some form of scenario or sensitivity analysis to determine the robustness of modelling consideration to changes in dimension weighting. Finally, as contemporary energy policies are formulated at the intergovernmental level, it is important that sustainability assessment is conducted at the intergovernmental level as well. The impact of a nation's energy generation decisions has global implication as ecological systems are shared by all nations. The Paris Agreement, a universal legally binding global climate deal comprising 195 countries in 2015 (European Commission, 2018), is an example of the recognition given to need for regional and international cooperation to build resilience and decrease vulnerability to the harmful effects on the environment. There is the need for a regional focus, with country-level assessment and benchmarking, if the impact of sustainable energy policies will be effective.

5. Conclusion

Evidence from the review shows a growing area of research with an inter-disciplinary and trans-disciplinary orientation attracting researchers from various backgrounds. Mapping and cluster analysis of co-occurrence of terms showed three dominant research themes – environmental analysis, evaluation methods and energy policy-related research interest. For the methods used, the dominant method is MCDM though other approaches exist. A variety of MCDM approaches have been employed. Also dominant are LCA-based researches that have seen extensive use in environmental impact assessment of energy generation systems. With the multi-criteria approaches are the problems of indicator selection and weighting of dimensions which can lead to a variety of outcomes based on the choice of the decision-maker. On the side of the issue, though different schools of thought on the substitutability of natural, economic and social resources have emerged over the years, the consideration of this has been limited in the literature. Other issues include the limited systems approach consideration outside LCA research when it comes to the sustainable operation of energy production systems and the restriction of most studies on national rather than multi-national basis.

The relevance of sustainability to researchers from a diverse array of academic disciplines has meant different considerations on the modelling and evaluation approaches. While this is a growing area of research, however, what constitutes sustainability and how it can be measured has become an important topic dominating such energy research. Though several definitions of sustainability exist, there is a recognition that sustainability assessment should provide global to a local integrated evaluation of economy-nature-society systems in short and long-term perspectives to assist in arriving at actions to make society sustainable. This calls for a systems perspective towards sustainability assessment of energy; such evaluation should not only include the energy system in a local context but also its global effects on economic, social and environmental systems. There is a need for traditional measurement approaches to be revised to be a better fit for sustainability assessment and provide more appropriate decision support for policy.

In essence, this work seeks new insights into modelling of systems with sustainability considerations. Though due to stakeholder pressure, sustainability has become an integral part of national and business discourse, modelling approaches employed in such decision support frameworks do not seem to have fully considered the various views espoused in sustainability literature. There is, therefore, the avenue for a newer and broader assessment of sustainability in energy generation. There is also the avenue for methodological contributions to be made in most of the current models used in multi-criteria problems when it comes to sustainability.

Declaration of competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2020.110464.

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