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Jingzheng Ren *Editor*

Energy Systems Evaluation (Volume 1)

Sustainability Assessment

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Jingzheng Ren
Editor

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Editor
Jingzheng Ren
Department of Industrial and Systems
The Hong Kong Polytechnic University
Hong Kong SAR, China

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Contents

Overview of Sustainability, Sustainable Development and Sustainability Assessment: Concepts and Methods

Yue Liu and Jingzheng Ren

Abstract Sustainability and sustainable development have gradually caused wide public attention during recent years due to the increasing concerns on resources and environment. The United Nations formulated and adopted a plan of action to promote the process of sustainable development, which covered 17 sustainable development goals and 169 specific targets to integrate and balance the three pillars of sustainable development. In order to provide a better understanding of the related concepts of sustainability, this paper provides an overview to introduce the relevant background knowledge and concepts on sustainability, sustainable development, and sustainability evaluation methods. Sustainability assessment methods are roughly classified into six major categories in this context, including individual or set of indicators, composite indicators, socially responsible investment indicators, energy and material flow analysis, life cycle sustainability assessment (LCSA) and multi-criteria decision-making (MCDM), and environmental accounting. Basic information on the method categories and related methods are summarized and presented according to the literature review. A qualitative analysis and comparison for the six sustainability evaluation method categories are carried out to assess the ability and potential for sustainability evaluation of these methods. Results showed that LCSA combined with MCDM can work as a reliable sustainability evaluation tool to provide a relatively complete assessment. Environmental accounting and individual or set of indicators are inferior to the other categories under the considered criteria system. Three suggestions are proposed based on the analysis to guide future research on sustainability evaluation from the perspective of comprehensiveness, involvement of stakeholders, and follow-up investigation.

Keywords Sustainability · Sustainable development · Sustainability assessment

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Y. Liu · J. Ren (✉)
Department of Industrial and Systems Engineering, The Hong Kong Polytechnic University, Hong Kong Special Administrative Region, Hong Kong, China
e-mail: jzhren@polyu.edu.hk

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1 Introduction

With the development of science and technology and the continuous growth of population, the total demand for resources is also increasing significantly. However, many resources that human being depends on are non-renewable resources, whose speed of renewal and regeneration cannot keep up with that of consumption. Meanwhile, the environmental problems caused by the incontinence of development accumulated and eventually led to the gradual deterioration of the environment in many regions. In order to face with the increasing resource and environmental problems and ensure the survival of the human race in the future, the concept of sustainability and sustainable development was proposed [18, 40]. It is an important concept as well as a principle of action that can even influence the development direction of a country and even the whole world.

Sustainable development is a goal for better development that can balance the relationship between the development of human society and environment. Hence, it can also be regarded as an indicator that can be evaluated to know about the extent to which it meets the requirement of sustainable development. Sustainability assessment is a critical project in the research related to sustainability and sustainable development. It can provide important reference for the relevant management and decision-making to achieve better sustainable development goal. Various methods have been proposed and developed for sustainability evaluation, such as life cycle assessment, energy, and material flow analysis, and cost–benefit analysis [4]. There are many literature reviews on sustainability evaluation methods or the evolution of sustainable development goals [29, 47], but the discussion on sustainability evaluation methods majorly focused on the application in specific domains, such as industrial water utilization [83], industrial systems [4], transport infrastructure projects [14]. Therefore, this paper intends to present a general overview on sustainability, sustainable development, and sustainability evaluation methods to promote the management and development in related fields.

In this chapter, a comprehensive literature review on the related concepts of sustainability and sustainable development is provided. Six major groups of sustainability evaluation methods are also briefly introduced and qualitatively compared based on the references. Three suggestions are proposed according to the discussion and analysis for the potential of sustainability evaluation methods, which can work as a reference to guide the future development of the studies on sustainability.

2 Methodology

The Scopus database [71] was applied to identify the articles characterized by related terms, such as sustainability review" and sustainability assessment/evaluation", in their title, abstract, and keywords. According to the database on Scopus [71], over 28,000 pieces of work regarding the topic of "sustainability" and "review" or

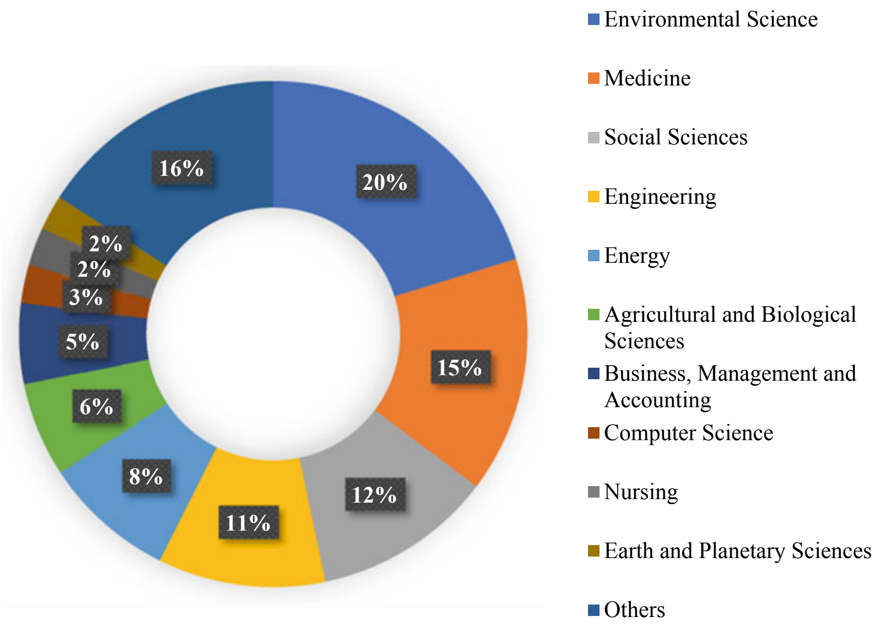


Fig. 1 Percentage contribution of reviews in different disciplines on "sustainability" and "review" or "overview"

"overview". Among this kind of studies, environmental science contributed the most which occupied about 17%. Social science and engineering also concerned a lot about the sustainability, which contributes about 14% and 11%, respectively. The energy field also focused on the related topics on sustainability, contributing about 8% among all the records (see Fig. 1). Figure 2 shows the increasing trend on the topic of sustainability reviews, which indicates the growing concerns on the relevant research on sustainable development. More investigations were conducted on "sustainability assessment/evaluation", nearly 50,000 records in the database on Scopus. It also presents an increasing trend on the research topic of sustainability" sustainability assessment/evaluation", which is shown in Fig. 3. Both the large amount and the rising trend indicate that the sustainability evaluation problem is getting more and more attention in the research field. Among the publications, research articles occupy the dominant position with 69%, while the reviews occupy about 7%. Similar to the overviews on sustainability, environmental science, social science, and engineering contribute the majority of the research on sustainability evaluation. 8,800 pieces of sustainability evaluation work were published in the energy field. All these data reveal the growing attention on sustainable development and related assessment, especially in environmental science, social science, engineering, and energy fields.

Since life cycle sustainability assessment (LCSA) is a powerful tool that is frequently applied in different fields for sustainability assessment, keywords "life

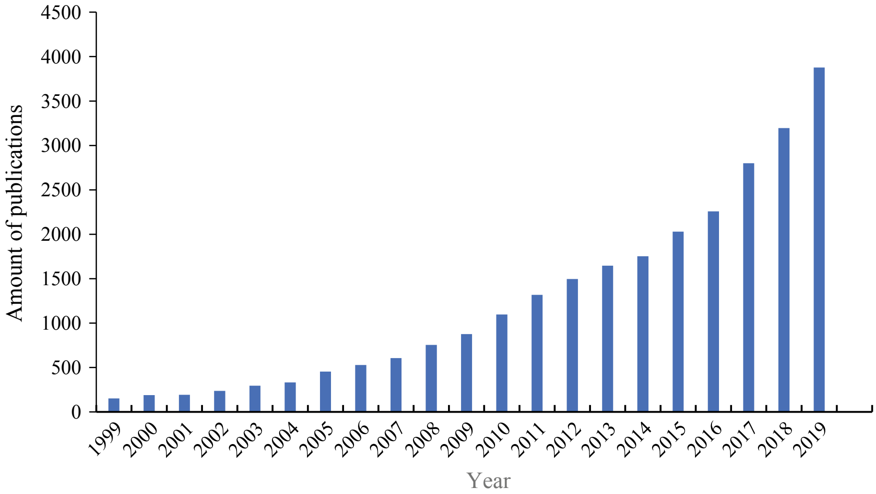


Fig. 2 Publications on "sustainability" and "review/overview" from 1999 to 2019 [71]

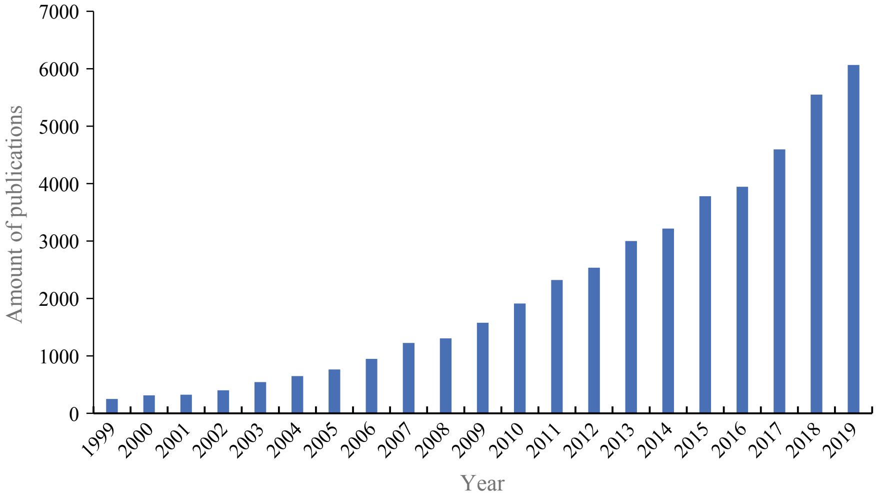


Fig. 3 Publications on "sustainability evaluation/assessment" from 1999 to 2019 [71]

cycle sustainability assessment" and "life cycle assessment (LCA)" were also investigated to analyze the research trend (see Fig. 4). There are over 7,000 related publications on LCSA or LCA during the recent two decades. Among all these publications, research articles occupy over three-fifths, while reviews take up about 7% with only 524 pieces of work. Environmrntal science, engineering, and energy take the top three

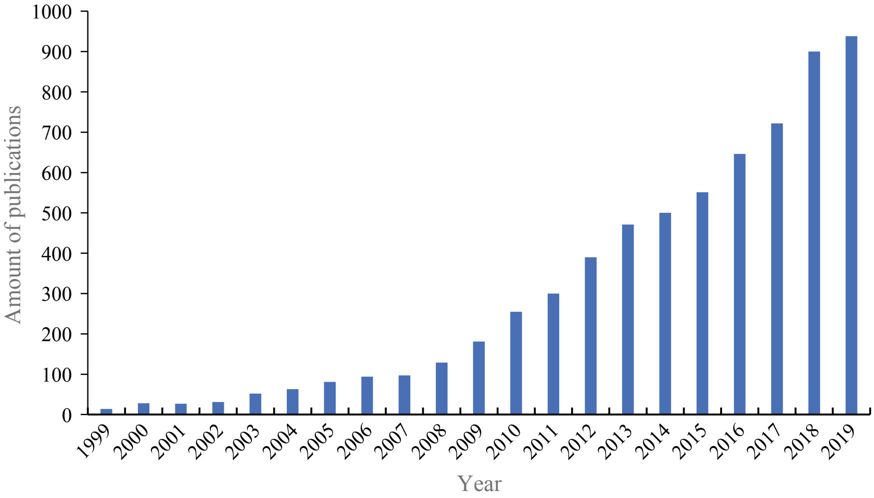


Fig. 4 Publications on “life cycle sustainability assessment” or “life cycle assessment” [71]

among the total related publications on LCSA or LCA, which indicates the close relationship between these disciplines and sustainability and the growing concerns on sustainability performances.

The importance attached to sustainability and sustainable development gradually increases according to the above data and discussion. Considering a large amount of related research and the limited reviews on sustainability assessment or evaluation (only about 5% of the total research), it is still necessary to conduct an overview to provide a clear framework on the related concepts of sustainability and sustainable development as well as sustainability assessment methods applied in different fields.

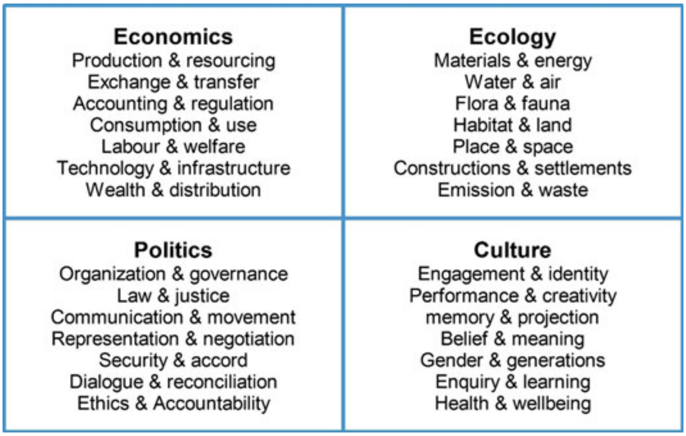
In this chapter, the reviewed articles were collected by Google Scholar, majorly from the database of Scopus. By using the keywords of “sustainability”, “sustainable development”, and “sustainability evaluation or assessment”, related studies were searched and filtered out. The title, keywords, and abstract were checked to verify whether the investigation can provide significant information on sustainability. If the articles present with useful knowledge, detailed content would be checked to collect the key points and form a systemic introduction for the concepts and evaluation methods of sustainability.

3 Literature Reviews

3.1 Sustainability and Sustainable Development

The term “sustainability” is derived from the Latin word “sustinere”, which means to hold up [55]. Sustainability refers to the process of maintaining the environmental balance and harmony in resource development, investment direction, technological development, and institutional change when the human being seeks social progress. Since the 1980s, the concept of sustainability has been frequently mentioned and discussed in different fields. The most widely recognized and accepted definition of sustainability is the one presented by the World Commission on Environment and Development (WCED). The definition points out that sustainable development refers to the development form which can satisfy the needs of current society without compromising the requirement of development for the future generation [18, 40]. Three pillars are often employed to address sustainability issues, including environmental, economic, and social [16]. Cultural, technological and political aspects are also considered as the sub-domains of sustainable development, which are presented in Fig. 5 [38, 50]. More recently, a new systematic domain model consisting of economic, ecological, political, and cultural four dimensions was proposed which accords with the United Nations, UNESCO, and Agenda 21, especially the culture as the fourth dimension of sustainable development [38].

Sustainability can be simply understood as improving the quality of human life within the capacity of the ecosystem [37]. Responsibility and proactive decision-making and innovation are usually required to reduce and minimize the negative influence and maintain the balance between ecology, economy, policy, and culture [50]. Different types of sustainability are included in sustainable development which



Economics Production & resourcing Exchange & transfer Accounting & regulation Consumption & use Labour & welfare Technology & infrastructure Wealth & distribution	**Ecology** Materials & energy Water & air Flora & fauna Habitat & land Place & space Constructions & settlements Emission & waste
Politics Organization & governance Law & justice Communication & movement Representation & negotiation Security & accord Dialogue & reconciliation Ethics & Accountability	**Culture** Engagement & identity Performance & creativity memory & projection Belief & meaning Gender & generations Enquiry & learning Health & wellbeing

Fig. 5 Four domains of sustainability adopted by the UN and metropolis association [38]

can be reflected by different fields, such as sustainable agriculture, sustainable architecture, and sustainable supply chain [20, 53]. Since the requirement of sustainable development is embodied in various fields, researchers have conducted relevant studies in order to achieve and promote better sustainability of the entire society. A critical review on sustainable development was presented and the existing problems were also discussed in the early 1990s [46]. The challenges and opportunities for sustainable development of current society were analyzed and summarized in the previous book [21]. The author also provided a relatively comprehensive introduction of the concept of "sustainable development" and the taken actions for current progress toward better sustainable processes and patterns, which can be regarded as considerable reference and guidance for future sustainable development. In order to further clarify the planning and task of sustainable development, specific sustainable development goals and targets were set and explained in the document of the United Nations, committing to achieving better sustainable development by 2030 [22]. Five priorities of the UN sustainable development goals were proposed including establishing metrics, building up monitoring systems, progress assessment, infrastructure improvement, and data standardization [47]. Metrics and evaluation approaches were emphasized in this comment since both items have an important influence on reflecting and assessing the extent of sustainability. This basic fact also indicates the significance of sustainability evaluation methods in sustainable development, which are introduced in the next section.

3.2 Sustainability Assessment Methods

Many efforts have been spent on sustainability evaluation and assessment either to establish new approaches, improve the existing methods or apply them in the case study. Plenty of assessment approaches have been built up and applied for sustainability evaluation in different aspects. Table 1 provides a brief summarization of previous studies and reviews on sustainability evaluation methods.

As it has been mentioned in the above literature review and presented in Table 1, life cycle analysis (LCA) and multi-criteria decision-making (MCDM) are also powerful tools for sustainability assessment. Considerable studies were conducted to apply LCA and MCDM-based approaches in sustainability evaluation or summarize the framework of the existing method based on LCA and MCDM. The discussion on integrated framework of LCA and MCDM for sustainability evaluation of renewable energy systems was carried out to analyze the application potential in this field by reviewing 154 relevant cases [15]. The analysis results showed that individually using LCA or MCDM could not realize a comprehensive sustainability assessment while the hybrid framework of these two tools could work as a satisfying approach for sustainability evaluation. The potential of five multi-criteria decision analysis methods, including Muti-Attribute Utility Theory (MAUT), preference ranking organization method for enrichment evaluation (PROMETHEE), ELimination Et Choice Translating REality (ELECTRE), and Dominance-based Rough Set

Table 1 Major information about related reviews and studies on sustainability evaluation methods

References	Major information about reviewed/research content	Number of reviewed methods
Angelakoglou and Gaidajis [4]	Sustainability assessment methods which can be applied for environmental performance evaluation by industries.	48
Sala et al. [66]	Provide an innovative and systemic framework for sustainability assessment to support the decision-making process.	N.A. (analysis)
Poveda and Lipsett [58]	Fundamental methods, specific and integrated strategies as well as credit weighting tools for sustainability evaluation in large industrial projects.	66
Singh et al. [72]	Sustainability indicators applied in decision and policy-making according to the classification.	61
Cinelli et al. [17]	Evaluate the potential of MCDM approaches on sustainability assessment.	5 (MAUT, AHP, PROMETHEE, ELECTRE, and DRSA)
Gibassier and Alcouffe [26]	Review and analyze the relationahip of EMA and environmental management controls (EMCS) with sustainability.	2
Campos-Guzmán et al. [15]	Sustainability evaluation tools which can be applied for renewable energy systems (focused on LCA and MCDM).	N.A.
Sala et al. [67]	Analyze the main characteristics of sustainability assessment methods and discuss the major aspects for improving the robustness and comprehensiveness of sustainability evaluation.	N.A.
Székely and Knirsch [73]	Review the best available indices applied by twenty German companies for sustainability evaluation.	13
Willet et al. [83]	Sustainability assessment methods applied in industrial water systems belonging to five categories were reviewed.	82
Turkson et al. [77]	Provide a systemetic review on the framework of sustainability assessment for energy production regarding the methods, measurement, and issues.	N.A.
Bueno et al. [14]	Provide a review for the sustainability assessment tools applied in transport infrastructure projects.	12
Luthra et al. [49]	Apply fuzzy AHP method to identify and rank the influencing factors to construct a sustainability assessment framework for energy management in India.	N.A.
Gil and Duarte [27]	Provide a review for the state-of-art of sustainability evaluation tools which can be applied in urban design and management.	11
Gbededo et al. [24]	Present a systemetic review on the sustainabille manufacturing methods (focused on LCA).	N.A.

Approach (DRSA), applied in sustainability evaluation was discussed alongside ten criteria which the sustainability assessment tools should satisfy [17]. The analysis results indicated that although all the five methods have the ability of processing uncertainty, robust results could only be obtained by the MAUT method. A review on social sustainability was carried out to discuss the research state of the art on social sustainability especially for the classical and emerging themes and assessment methods [19] which pointed out that social impact assessment was frequently applied in the social sustainability assessment. Through analyzing the progress in sustainability science and existing sustainability evaluation methods, Sala et al. [67] pointed out that lifecycle-based methods and LCSA make a significant contribution to sustainability evaluation. The strengths and weaknesses of utilizing life cycle sustainability assessment were investigated from the ontological, epistemological, and methodological aspects [68]. The state of the art of LCSA for products was analyzed by Kloepffer [41] and the research revealed that environmental LCA and life cycle cost (LCC) have a relatively complete research foundation while social life cycle sustainability assessment (SLCA) is still under development. The researcher suggested that the combination of LCA, LCC, and SLCA can provide powerful tools for sustainability evaluation of products. By reviewing 340 papers on sustainability assessment for industrial water application, 82 methods were identified which were further classified into five major categories, including key performance indicators, composite indices, environmental accounting, material and energy flow analysis, and life cycle analysis [83]. The authors found that material and energy flow analysis presents a satisfactory performance combined with sustainable systems indicators (SSIs). Bond et al. [9] also conducted a analysis for the development state of the art of sustainability evaluation methods and assessed the basic performance of these approaches from six criteria. Except for MCDM and LCA, exergy analysis and other optimization-based methods, like multi-objective optimization model, can also be applied for sustainability assessment [77]. Bueno et al. [14] presented an overview of the existing sustainability evaluation tools applied in the transport infrastructure discipline, which still majorly focused on LCA, MCDM, and cost–benefit analysis (CBA). Sustainability evaluation tools applied in urban design were identified and reviewed according to an analytical framework that covered the format, structure, content, and output [27]. Among the various MCDM methods, the analytic hierarchy process (AHP) and its extended or improved approaches were often applied in sustainability evaluation [5, 39, 63]. According to the analysis of Luthra et al. [49], the environmental dimension was regarded as the most important dimension for sustainability evaluation in energy management in the context of Indian. Through employing the fuzzy AHP method, the authors formed an integrated sustainability evaluation framework to rank the related indicators. A weighting system based on AHP and plenty of inputs from experts in different domains was built up for sustainable assessment in the built environment in Saudi Arabia [3].

In order to provide a clearer summary and facilitate the related analysis on the assessment approaches, it is necessary to figure out the categories of the methods. There is no unified classification standard for sustainability assessment methods. The researchers usually classified the evaluation approaches according to their research purpose and focused field. Several classification approaches for the evaluation methods are summarized in previous reviews [4, 72, 83] and shown in Table 2.

Since the major focus of this chapter is on environmental sustainability and sustainable development of energy industries, the sustainability evaluation methods are classified into the following six categories based on the previous reviews [4,

Table 2 Classification of sustainability assessment methods in different references

Reference	Classification	Standard of classification
Ness et al. [54]	(i) Indicators (integrated and non-integrated); (ii) Methods that are product-oriented; (iii) Methods which are project- and policy-oriented.	According to the applied indicators and objectives.
Poveda and Lipsett [58]	(i) Generic methods; (ii) Strategic methods; and (iii) Integrated approaches.	According to the function and objective.
Gasparatos [23]	(i) Reductionist methods; and (ii) Non-reductionist methods.	Whether the method is reductionist or not (broad general categories).
Székely and Knirsch [73]	(i) Surveys; (ii) Criteria of stakeholders; (iii) Reward projects; (iv) Benchmarking; (v) Sustainability indices/indicators; (vi) External communication approaches; (vii) Accreditation procedures; (viii) Sustainability performances metrics; and (ix) Non-quantifiable alternatives.	According to the conducting core thought.
Angelakoglou and Gaidajis [4], Willet et al. [83]	(i) Indicators set; (ii) Composite indices; (iii) Socially responsible investment indicators; (iv) Energy and matters flow analysis; (v) LCA; and (vi) Environmental acconting.	According to the focus and research purpose.
Singh et al. [72]	(i) Economic approaches; (ii) Physicial indicators.	Whether the method is economiy-oriented.
Turkson et al. [77]	(i) MCDM methods; (ii) Exergy analysis; (iii) LCA; (iv) Optimization-vased methods.	According to the core thought.
Bueno et al. [14]	(i) Conventional decision-making methods (CBA, MCDA, LCA, SCLA, etc.); (ii) Sustainability rating systems; (iii) Other approaches which can address the sustainability appraisal (e.g., framework, guidlines, models).	N.A.

83], where MCDM is combined with the category of LCA since they are frequently applied together especially in the research related to sustainable energy development. The basic introduction, such as definition, features, advantages, and disadvantages, of each category is summarized and shown in Table 3. Some typical examples of sustainability assessment methods belonging to different categories according to the classification and corresponding information of each method are presented in Table 4. More detailed introduction can be found in the related references and previous reviews [4, 58].

In order to have a better understanding of potential and ability of the different sustainability evaluation methods in sustainability assessment, an analysis and comparison alongside several important criteria is conducted in the next section to investigate the performance of different sustainability evaluation methods.

4 Methods Comparison and Discussion

Due to the existence of a large number of sustainability assessment methods, it would be difficult to conduct comparison and evaluation by methods because it could require plenty of data, time, and efforts. Meanwhile, evaluating by methods may only be applicable to a limited number of methods and lose the generality to the other approaches. Therefore, evaluation of the sustainability assessment approaches conducted by categories is suggested to keep the generality and cover a wider range of methods, which can also contribute to the improvement of the assessment methods [4]. In order to investigate the ability and potential of different sustainability evaluation methods, a reliable criteria system is necessary for evaluation. Different research may build up the assessment system by considering different criteria due to the diverse focus and research objectives. Some criteria considered in previous studies have been summarized in Table 5. A more detailed description can be found in the corresponding references.

According to Table 5, some common criteria can be found in different references as the key points for the evaluation toward sustainability assessment methods, such as the effectiveness of indication on sustainability performance, potential of further improvement on sustainability performance, and applicability. In this work, a criteria system for the evaluation of sustainability assessment methods is built up based on the above literature review. The classification of the criteria applied in this work follows the categories proposed by Bockstaller et al. [8], including scientific soundness, feasibility, and utility. Detailed criteria framework and corresponding description are shown in Table 6.

These criteria are selected to evaluate the potential of sustainability assessment methods from the perspective of the features of methodology, application, and learning dimension. The indicators of methodology perspective can address the inherent characteristics of the corresponding methods, such as the comprehensiveness (the number of addressed pillars), the ability of treating uncertainty and the involvement of stakeholders. Sustainability assessment problems can be complex in

Table 3 Brief description of different categories of sustainability evaluation methods

Category	Definition	Remarks
Individual/set of indices	The methods that use a single or a set of indices to address the sustainability performance on different aspects [4].	– Also be regarded as key performance indicators (KPIs) if the indicators are choosed according to predefined organizational objectives and applied for progress evaluation on the major aspects of the investigated systems.
Composite indicators	The methods that diverse indicators are combined and used in a defined methodology as sub-indices or a signle index for sustainability evaluation [4].	– Involving steps include normalzation, weighting, and aggregation. – The maajor calculation process could be subjective. Uncertainty and sensitivity analysis are usually combined to help improve the robustness of the methods [72].
Socially responsible investment (SRI) indicators	The methods based on the indices which are frequently applied by external staeholders to evaluate sustainability performance for the concerned customer industries [4]. SRI may also be defined as a type of investment discipline or style, which is attached with more importance on social or environmental aspect [64].	– It can work as social indicators to address the social and economic sustainability performance and be combiend with composite indices [4]. – SRI indicators can help to promote ethical and socially concerned issues, such as environmental sustainability, social justice, and corporate ethics [64].
Energy and materials flow analysis (EMFA)	The methods address sustainability performance through quantifying the material and/or energy flows of the investigated systems [4].	– Can be futher classified into material flow analysis (MFA) and energy flow analysis (EFA) [4]. – The principle of this category of methods is the law of investigation of mass and energy to evaluate the flows of concerned materials and energy. – The combination of EMFA and LCA can improve accuarcy and relevance.
Environmental accounting	The methods address sustainability performance through converting the environmental costs and benefits to economic value [4, 83].	– The category of methods can contribute to the evaluation process if the monetization of ecosystem services is relatively complete and can be fully captured [83]. – Lack of obligatory independent assessment can limit the reliability and quality of the assessment results obtained from EA [83]. – Can be combined with other methods and further improve the effectiveness [28].

(continued)

Table 3 (continued)

Category	Definition	Remarks
LCA & MCDM	LCA refers to the methods that invlove life cycle thinking [4]. MCDM methods can assess the examined alternatives under multiple conflicting criteria.	– LCA shows the advantage on providing a comprehensive and stuctured evaluation on the enironmental impacts and benefits. However, it fails to assess different systems in different scales and regions and is also easy to be limited by other conditions beyond geographic system boundaries [83]. – MCDM or MCDA is a powerful tool to conduct ranking and sustainability evaluation for diverse systems due to the flexibility and ability of dealing with the interactions and dialogue between stakeholders [17].

the practice especially when plenty of conflicting factors and interests are considered in the evaluation. Therefore, it is expected that the sustainability assessment methods could be widely applicable with acceptable stability. Indices in application aspect reveal the convenience level in practical applications. Software support and ease of use can help to describe the convenience of applying the assessment methods. Graphic representation can provide more intuitive information and assessment results which may contribute to the understanding of the final evaluation results for stakeholders, especially those without professional background knowledge. Learning dimension is also an essential aspect for the sustainability evaluation approaches since it indicates the evaluation ability and implication for better sustainable development and management in the related field in the future, which is a major focus of this kind of research. Stakeholders also expect to learn more information from the assessment result in order to guide the future development of the related industry. According to the criteria system and corresponding checklist, the number of asterisk (*) indicates the potential and ability for sustainability evaluation of the investigated methods categories. More asterisks mean higher potential and ability on sustainability assessment.

After the establishment of the criteria system, qualitative analysis and comparison for the sustainability assessment methods categories can be conducted accordingly. The detailed results are presented in Table 7.

4.1 Assessment Results on Scientific Soundness

The ability of revelation on the sustainability performance on the three sustainability pillars including environmental aspect, economic aspect, and social aspect, is regarded as the comprehensiveness of the sustainability assessment method category. Except for energy and matters flow analysis and environmental accounting, the

Table 4 Brief description of different sustainability assessment methods

Category	Assessment approach	Description
Indicators set	IChemE sustainable development progress metrices (IChemE)	Provide measurement for sustainability performance of industrial facilities in different scales by a set of indicators.
	Indicators of sustainable production (ISP)	Based on a group of major and supplemental indicators which can contribute to the measurement of sustainable production systems [79].
	Sustainability assessment framework for industries (SAFI)	Provide general guidance for the selection of assessed criteria among reliable and objective sustainability evaluation [45].
Composite indicators	AIChE sustainability index (AIChE SI)	Evaluating the sustainability performance of an industry based on seven sustainability-oriented categories [4].
	BASF method (BASF)	A cradle-to-grave assessment which investigates the environmental behavior and influence on human health and ecosystems stability [69].
	Compass index of sustainability (COMPASS)	Evaluating the sustainability of investigated industry through four aspects, inclufing nature (N), economy (E), society (S), and well-being (W) [4].
	Compliment Index (COMPLIMENT)	A comprehensive method for sustainability assessment which combines LCA, multi-criteri analysis, and evironmental indicators [32].
	Other methods	More summarization on composite indicators can be found in the previous reviews [4, 72].
Socially responsible investment indicators	Dow–Jones sustainability Index (DJSI)	Predefined sustainability criteria are applied to evaluate sustainability performance of the industries according to a best-in-class method [62].

(continued)

Table 4 (continued)

Category	Assessment approach	Description
	FTSE4Good Index (FTSE)	A method to evaluate the performance on industries which satisfy the globally accepted responsibility standards and find out the industries with outstanding performance on environmental aspect [4].
	OEKOM Corporate Rating (OEKOM)	A method to evaluate and prioritize industries based on their environmental and social sustainability performance [4].
Energy and matters flow analysis	Material flow analysis: ecological footprint (EF), material inputs per service and ecological rucksack (MIPS), substance flow analysis (SFA), etc.	1. EF method assesses the requirement of theoretical area in global hectares for consumed resources production and wastes assimilation [81]. 2. MIPS method assesses the possible environmental influence of the useful output of a product with respect to its material and energy input [52, 70]. 3. SFA method detects and monitors the flows of substances that put considerable impact on environmental and health risks during their production and consumption process [12, 34].
	Energy flow analysis: cumulative energy demand (CED), embodied energy (EE), emergy analysis (EA)	1. CED method evaluates the performance of the investigated system based on the estimation of the direct and indirect energy consumption throughout the entire life cycle (i.e., extraction, Treatment, and disposal) [35]. 2. EE method evaluates the sum of the direct and indirect energy consumption for the production of a specfic product/service [10, 11]. 3. EA method estimates the energy consumption of one kind (usually refer to the solar energy) in transformation to produce a product/service including direct and indirect way [11].
Environmental accounting	Cost–benefit analysis (CBA)	A method provides specific calculation procedure to examine the benefits and costs of the investigated process or project [31, 58].

(continued)

Table 4 (continued)

Category	Assessment approach	Description
	Contingent valuation method (CVM)	A survey-based approach which evaluates the willingness to pay or accept for environmental improvements or environmental quality reduction [58, 80].
	Environmental management accounting (EMA)	A general method which evaluates environmental and economic performances through assessing environmental costs accounting and physical environmental flows analysis [4, 26].
Life cycle sustainability analysis (LCSA) & MCDM	Signle aspect/generic framework: Briges to sustainability (BRIDGES), Carbon footprint (CF), Ecosystem Damage Potential (EDP), Life cycle sustainability dashboard (LCSD), USES-LCA	1. BRIDGES: a general assessment framework to evaluate environmental, economic and social sustainability performance covering multiple life cycle stages. It emphasizes the importance of resource scarcity, overabundance, and possible influence [7]. 2. CF: an estimation method of greenhouse gases emissions expressed in CO_2 equivalents [56]. 3. EDP: a model can assess the impact on ecosystems resulted from land occupation and land transformation [42, 43]. 4. LCSD: a method with general guidelines for the revision to benchmark the products' sustainability [76]. 5. USES-LCA: a method of impact evaluation of exotoxicity and human toxicity on both midpoint and endpoint levels [36, 78].

(continued)

Table 4 (continued)

Category	Assessment approach	Description
	Multi-impact assessment (CML 2001, Eco-Indicators 99, EDIP 2003, EPS 2000, IMPACT 2002+ , LIME, ReCiPe, TRACI)	1. CML 2000, IMPACT 2000 and ReCipe are frequently used in evaluation for renewable energy [15]. 2. Climate change, acidification, and photooxidants formation are three often considered indicators for renewable energy assessment [15]. 3. CML 2001 replied a midpoint approach based on the standards of ISO 14,040, while Eco-indicator 99 folows an endpoint method [15]. 4. EDIP 2003: a midpoint method concerntrated on damage assessment. 5. EPS 2000 evaluates five impact categories on midpoint and endipoint. 6. Impact 2002+ combines IMPACT 2002, Eco-indicator 99, CML, and IPCC approaches considering both midpoint and endpoint.
	Life cycle costs (LCC) and social life cycle sustainability assessment (SLCA)	LCA, LCC, and SLCA address the sustainability performance on environment, economy, and society, respectively [18, 19, 68].
	MCDM (Multi-attribute decision- making, MADM; Multi-objective decision-making, MODM)	1. MADM focuses on the decision-making problems with finite alternatives while MODM considers more than two alternatives. 2. Criteria: technical, economic, environmental, social [15, 82]. 3. Weighting methods: subjective weighting methods, objective weighting methods, and combination of both [82]. 4. Multi-criteria decision analysis: elementary methods, unique synthesizing criteria methods, and the outranking methods [17, 82]. 5. Frequently applied methods: AHP and related combination or improved methods, TOPSIS, and VIKOR [15]. 6. Combined with other theory or tools: fuzzy theory [1, 51], Data Envelopment Analysis (DEA), grey relation analysis, etc. [59].

Table 5 Evaluation criteria for the sustainability assessment methods in different references

References	Criteria
Angelakoglou and Gaidajis [4]	1. Potential of promoting actions for improvement 2. Potential of helping with the decision-making process 3. Potential for benchmarking 4. Applicability and convenience of application 5. Integration of wider spatial and temporal features
Sala et al. [66]	1. Boundary-orientatedness 2. Comprehensiveness 3. Integratedness 4. Involvement of stakeholders 5. Expansibility 6. Transparency 7. Core thought of the evaluation method
Cinelli et al. [17]	1. Applicability of qualitative or quantitative data 2. Whether the method can be conducted with life cycle thinking 3. Weighting approach 4. Application of thresholds values 5. Conpensation extent 6. Uncertainty and sensitivity analysis 7. Robustness 8. Software support and graphical illustration 9. Convenience of application 10. Educating dimension
Sala et al. [67, 68]	1. Core thought of the assessment method (value choices, scopr's completenss, strategicity) 2. Features of the method (integratedness, applicability and comparability, robustness, involvement of stakeholders)
Bond et al. [9]	3. Effectiveness on the procedures 4. Effectiveness on the factual outcomes 5. Transactive effectiveness 6. Effectiveness on normalization 7. Satisfactory of the related parties 8. Potential of promoting the related knowledge and information
Bueno et al. [14]	1. Full approach (can evaluate the three sustainability dimensions) 2. Life cycle thinking (investigate the entire life cycle) 3. Reliable methodologies for the comparison of all trade-offs 4. Flexibility and adatability to the aplied context 5. Transparency

other sustainability assessment method categories possess the potential of providing a comprehensive sustainability assessment on the three aspects. The former three method categories can reflect the performance on the three pillars by selecting indicators related to the corresponding aspect, such as emissions for environmental impact, monetary efficiency for economic analysis [4], and education for the social impact [74]. The inherent framework of LCSA has provided the assessment for the three aspects, that is LCA (environment), LCC (economy), and SLCA (society) [18].

Table 6 Criteria system for evaluation of the sustainability assessment methods

Aspect	Criterion/issue	Checklist
Scientific soundness	C1: Can methods indicate the sustainability performance on the three pillars (environment, economy, society)[1]	Only one of the three pillars (*), two of the three pillars can be address (**), three pillars (or more) can be addressed (***)
	C2: Can methods be conducted alongside life cycle thinking?[2]	No (*), Yes (**)
	C3: Can methods be applied at small or medium scale and address the sustainability performance across time?[3]	Neither of them is satisfied (*), only one of the conditions can be satisfied (**), both conditions can be satisfied (***)[4]
	C4: Ability and effectiveness of treating uncertainty[2]	Can be combined with other methods for uncertainty analysis (*), inherent properties of the methods allow them handle the uncertainty (**)
	C5: Involvement of stakeholders[1,3]	Basic communication (*), and basic interactionsi in serveral specific stage (**), and close interactions along all stages (***)[1,3]
Feasibility	C6: Can methods easily be applied by non-professionals?[4]	No (*), Yes (**)
	C7: Whether methods have software support?[2]	No (*), Yes (**)
Utility	C8: To what extent can methods promote the further improvement and sustainable development of the investigated systems?[4]	No promotion or low promotion (*), can offer useful suggestions for the promotion (**), can provide effective suggestions for better sustainable development (***)[4]
	C9: To what extent does the sustainability assessment methods promote the conceptual learning?[5]	Relatively low (*), medium (**), relatively high (***)

[1] Sala et al. [67]
[2] Cinelli et al. [17]
[3] Sala et al. [66]
[4] Angelakoglou and Gaidajis [4]
[5] Bond et al. [9]

MCDM can also assess the investigated system from the three sustainability dimensions through constructing a criteria system covering all the aspects [82]. Although energy and material flow analysis can promote the development on the socioeconomic and environmental aspect through investigating the material and energy flow efficiency [34], the category of assessment methods focuses more on environmental and economic aspects. Similarly, environmental accounting methods are more inclined to address the sustainability performance from environmental and economic perspectives [4], which makes it less prior in the criterion of comprehensiveness.

Table 7 Qualitative evaluation for the sustainability assessment method by category

Aspect	Criterion	Indicators sets	Composite indices	Socially responsible investment indicators	Energy and matters flow analysis	LCSA and MCDM	Environmental accounting
Scientific soundness	C1	***[1, 2]	***[1, 3]	***[1]	**	***[5]	**[1]
	C2	**[1, 6]	**[1, 7]	**[5]	**[8]	**[5]	**[6]
	C3	**[1]	***[1]	**[1]	***[1]	***[1, 7]	**[10]
	C4	*	*	*[9]	*	**[11]	*[12]
	C5	*	*	*	*	*[13]	*
	Total	9	10	9	9	11	8
Feasibility	C6	**[1]	**[1]	**[1]	*[1]	*[1]	*[1]
	C7	*[1]	*[1]	*[1]	**[1]	**[1]	**[1]
	Total	3	3	3	3	3	3
Utility	C8	**[1]	**[1]	**[4]	***[1]	***[1]	**[1, 4]
	C9	*[1]	***[1]	**[1]	**	***[4]	**
	Total	3	5	4	5	6	4
Overall score		15	18	16	17	20	15

[1] Angelakoglou and Gaidajis [4], [2] ALwaer and Clements-Croome [2], [3] Talukder et al. [74], [4] Willet et al. [83], [5] Campos-Guzmán et al. [15], Ciroth et al. [18], [6] Azapagic and Perdan [6], [7] Hermann et al. [32], [8] Rincón et al. [61], [9] Koellner et al. [44], [10] Bueno et al. [14], [11] Geisler et al. [25], Guo and Murphy [30], [12] Ludwig et al. [48], [13] Sala et al. [66]

As for the life cycle thinking aspect, all the categories can be conducted alongside life cycle thinking to analyze the sustainability performance in the whole life stages. It is an inherent requirement for LCSA to conduct the sustainability analysis with life cycle thinking while others may not necessarily proceed with the life cycle approach.

The scalability of sustainability assessment methods can influence their flexibility and applicability. Those with higher scalability can usually be applied on a wider scale and more flexible manner. However, some methods may have requirements on the data scale which would limit the applicability to small or medium scale industries. According to the analysis of Angelakoglou and Gaidajis [4], individual or set of indicators and environmental accounting can be applied on a small or medium scale, while the others without the applicability in such range. LCSA usually can be applied on a relatively large scale such as in urban or national context, but generally, it is not applied on a larger scale like global range due to the specific features in different regions. The assessment results obtained by LCSA still significantly influenced by the features of the investigated region and assumptions on the examined systems [75].

Uncertainty analysis and sensitivity analysis are usually important sections in the sustainability assessment due to the uncertainty introduced by the imported data and subjective language descriptions. All the methods of categories have the potential of treating the uncertainty in the evaluation by combined with interdisciplinary theory, such as probability theory [30], stochastic process, and Monte Carlo method [57]. Reversely, some MCDM methods are supposed to have the potential to deal with the uncertainty by inherent features [13, 17]. Fuzzy theory combined with MCDM, which is so-called fuzzy MCDM, can also help with uncertainty treatment [33, 51]. Most of the methods can be adequate for uncertainty treatment although varying with extent.

Both sustainability assessment and decision-making processes have a close relationship with stakeholders. Timely feedback and full interaction contribute to better collection and acquisition of information and understanding the demands of stakeholders [67]. However, most of the methods show disadvantages on the participation of stakeholders[66, 67]. The involvement of stakeholders in current sustainability assessment methods is mainly limited in the criteria system constructing stage and weighting stage. This disadvantage is obviously reflected in lifecycle-based methods since the development of this kind of method for the involvement with stakeholders remains in the early stage [67].

4.2 Assessment Results on Feasibility

Ease of use reflects the complexity, acceptance, and applicability degree to non-professionals of the sustainability methods. Some methods can be easy to understand and convenient to operate even without professional training, like AHP approach [65] and best–worst method [60], while some could be difficult for non-experts to get started. The former three evaluation method categories share a similar complexity level and are frequently applied by industries, especially the individual or set of indicators [4]. LCSA and energy and material flow analysis requires reliable data analysis which may increase the time and effort spending on sustainability evaluation by these two types of categories. The challenge that environmental accounting facing is to convert diverse environmental parameters into monetary costs, which can be difficult to employ without clear guidance [4].

Although the latter three method categories are inferior in the complexity, the software support and graphic representation can counteract the negative effects generating from the complexity to some extent, such as the database (GaBi, and Ecoinvent) for LCA, Sankey diagram for energy and material flow analysis, and some available tools for environmental accounting (Greenbase, Botkeeper, and Sphera).

4.3 Assessment Results on Utility

It is critical for the sustainability evaluation method to clearly indicate the sustainability performance of the investigated system and promote the management and development of the related industry. This issue is evaluated by the ability and potential of promoting actions of improvement of the sustainability assessment methods category [4]. If the method category can promote the future sustainable development of the examined system by the assessment results analysis and related implications, it can be regarded as a useful and potential tool for facilitating the related management and better sustainable development for the industry. Most of the methods in the categories can provide a reference for management by indicating the assessment results and conducting related actions to reduce environmental impact or improve energy efficiency. It is recognized that both LCSA and MCDM can provide relatively reliable sustainability evaluation [4, 15]. LCA with ISO 14,040 framework can provide a partial sustainability evaluation while LCSA can provide a complete evaluation because the three sustainability dimensions are all covered. Similarly, MCDM can also be a reliable complete sustainability evaluation tool due to the consideration of the three pillars. The combination of LCA (or LCSA) with MCDM can achieve a relatively satisfactory evaluation effect with the completeness of the considered aspects and the objectivity provided by LCA [15]. Hence, more implications and targeted measures can be proposed according to the assessment results obtained by LCSA and MCDM. Energy and material flow analysis can offer useful suggestions for improving some critical energy or materials efficiency to promote better management in some specific industries. Other categories are also possible to provide valuable help for sustainable development through their specific feature, which can be referred to in the review of Angelakoglou and Gaidajis [4].

The learning dimension of the sustainability evaluation method is mainly reflected by the ability of revelation on the information and conducting cross-comparison among different industries. All the method categories can reveal the sustainability information of the investigated system to a different extent, which has been mentioned in the above discussion. Cross-comparison is an important aspect of sustainability research especially for finding out better sustainable strategies. Life-cycle-based methods show the advantages on cross-comparison since all the influence in the entire life stages are considered, which make the comparison between different systems be possible. Relatively speaking, methods included in individual or set of indicators are inferior in this aspect [4]. Bond et al. [9] analyzed the merits and shortcomings of knowedge and learning aspect of current sustainability practice. Their analysis pointed out that although the methods can promote the implementation of sustainable policy and planning in related industries, the follow-up investigation on the system is limited, which means that more efforts are still needed for further practice and reflection.

4.4 Discussion and Implications

An overall evaluation result of the examined sustainability assessment categories can be obtained based on the above analysis and discussion, which shows that LCSA and MCDM can perform as a reliable sustainability evaluation tool, followed by

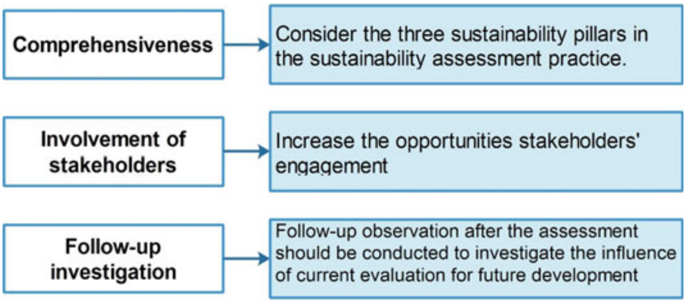


Fig. 6 Suggestions for the future development of sustainability evaluation methods and sustainability assessment practice (modified from [9])

composite indices and energy and materials flow analysis. Individual/set of indicators and environmental accounting are not preferred according to the evaluation results in the context of this paper due to the unsatisfactory performance on scientific soundness and utility. The qualitative evaluation results in this paper are similar to the analysis of previous study [4], which also indicated the advantage of LCA. The difference between the evaluation results may be resulted from the difference between the evaluation system and inspection criteria. The sustainability evaluation ability of LCA and MCDM has also be recognized by Campos-Guzmán et al. [15] through detailed analysis and comparison. Hence, it can be found that the potential of LCSA and MCDM for sustainability assessment has been gradually recognized and accepted.

Some limits and shortcomings can be found based on the above analysis and discussion. Suggestions are accordingly proposed to promote the improvement and development of the sustainability evaluation methods in order to achieve better sustainable development (see Fig. 6).

There are three major points for developing reliable sustainability evaluation methods and conducting more convincing sustainability assessment research. On the one hand, the comprehensiveness of the sustainability evaluation should be further improved [9]. Although many methods are possible to provide the framework to assess the performance of the three sustainability pillars, the majority of studies still focused more on environmental and economic dimensions while the social impact is relatively less investigated. Some approaches may even not cover the other aspects beyond environmental and economic perspectives. The study of Gbededo et al. also revealed that less than 30% of the reviewed 54 papers conducted the sustainability assessment on the three sustainability dimensions [24]. It reflects that the consideration of integrated sustainability index is still limited in the current work. Therefore, comprehensiveness is necessary to improve in the future development of sustainability evaluation. On the other hand, the involvement of stakeholders is still limited in the principle of assessment methodology, especially the life-cycle-based approaches [67]. MCDM is possible to offer more chances for stakeholders and experts to participate in the assessment and decision-making process [82]. However, other methodology categories show disadvantages on this aspect to a different extent [66]. Hence, increasing the opportunities for stakeholders' involvement for better negotiation and understanding is also one of the future tasks. In addition to these two aspects, as it has been mentioned in the above sections, follow-up investigation to observe the process of the examined system and the long-term sustainability performance is scarce in the current evaluation practice. Some evaluation methods can only provide immediate sustainability consequences other than long-term impact analysis. Sustainability is a concept that has a close relationship with time. Thus, the ability to evaluate sustainability over time and long-term investigation for the examined alternatives are essential to contribute more reliable sustainability evaluation results. According to the above discussion, more efforts are still expected to further improve the effectiveness and reliability of sustainability evaluation methods for the better sustainable development of the related industries and even for the whole society.

5 Conclusions

The related concept of sustainability and sustainable development were reviewed in this article. Sustainability evaluation methods were qualitatively analyzed by category, including individual/set of indicators, composite indicators, socially responsible investment indicators, energy, and material flow analysis, LCSA and MCDM, and environmental accounting. Three perspectives and nine criteria were considered to construct the criteria system for methods evaluation, covering scientific soundness, feasibility, and utility. According to the literature review and assessment results, LCSA and MCDM are relatively reliable tools for sustainability evaluation, and the combination of both works better which can provide a complete sustainability evaluation [15]. Composite indicators and energy and material flow analysis are also acceptable evaluation methods. The performance of the other three method categories was not so satisfactory which means that they show some disadvantages on the considered criteria at different degrees. Based on the literature review and evaluation results, three limitations and suggestions were proposed accordingly to guide the future development of related research on sustainability evaluation methods and sustainability assessment practice. These three points include comprehensiveness, the involvement of stakeholders, and the long-term investigation for the target systems of the sustainability assessment methods. Future research may consider these three directions to improve current sustainability evaluation methods. Although there are powerful tools for sustainability evaluation, some challenges still exist in the practice, like the unfeasibility of exact data on social and technical aspects, which can be a major barrier for conducting sustainability evaluation considering all the sustainability pillars. More efforts are still expected to complete the framework of sustainability evaluation methods and related databases.

This work only carried out a qualitative assessment for the sustainability evaluation methods. A case study is suggested for more accurate and targeted analysis and comparison if evaluating the performance of several specific methods, which can also be a working direction for future research to provide a reference for method selection.

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Integrated Sustainability Assessment of Energy Systems at the Macro Level

Huijuan Xiao and Jingzheng Ren

Abstract The sustainable development of the energy systems of China is becoming increasingly significant for both current and future generations. However, most of the existing studies focus on the evaluation of the energy system at the micro-level, which is a specific kind of energy type (e.g., hydrogen energy systems and electricity generation systems), with the energy system at the macro level missing. This neglect will set a barrier for the policymakers to better understand the situation of the whole energy system of China. To fill this gap, this study firstly constructed a framework of the energy system at the macro level, which is an integration of four important sub-systems, including energy construction system, energy production system, energy transformation system, and energy consumption system.15 criteria are then selected to evaluate the sustainability of the energy systems of Chinese 30 provinces from 2013 to 2017. Lastly, to further analyze the energy system structure types of each province, this study used the Q-type cluster method to group the 30 provinces into three categories. Some targeted policy implications are then proposed based on the sustainability evaluation results as well as the classification results. This study finds that (1) the sustainability of the whole energy system still has much room for improvement. Beijing (0.70) was the best performer of the whole energy system in 2017, while Ningxia (0.42) was the worst performer; (2) there is great inequality in the energy transformation system. Beijing has a much high level of sustainability in the transformation system, while the sustainable levels of the rest of the provinces are far from enough. Policymakers should not only place more emphasis on the improvement of sustainability of the energy transformation system but also on the reduction of the inequality in transformation system by technology diffusion from Beijing, and (3) based on the clustering result, Beijing always belongs to group one and has a relatively more sustainable energy system. However, Shanxi,

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H. Xiao · J. Ren (✉)
Department of Industrial and Systems Engineering, The Hong Kong Polytechnic University, Hong Kong Special Administration Region, China
e-mail: jingzheng.jz.ren@polyu.edu.hk

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Hunan, Inner Mongolia, Qinghai, Ningxia, and Xinjiang have similar patterns of low sustainability of the energy system. It can be interpreted some of these provinces are abundant in energy resources and are manufacturing-based provinces. The relatively low value-added and energy-intensive industry could damage the sustainability of the energy system.

Keywords Energy system · Sustainability assessment · Energy indicator system · Cluster analysis · Best-worst method

1 Introduction

A major topic among the current researches on energy is the sustainability of energy development [12–15]. Promoting the sustainability of the energy system becomes increasingly significant for policymakers around the world [24]. To be sustainable, an energy system must meet the needs of residents without compromising a region's livability—including mobility, health, and safety—or the ability of future generations to meet their needs. Currently, China's energy consumption has influenced the energy demand on a global scale significantly, since China has become both the largest energy consumer and CO_2 emitting country in the world [5]. The rapid increase in energy consumption should be accompanied by a high energy supply, including producing from the domestic energy system or importing from other countries. It is of great significance to increase the sustainability of the energy system in China.

In recent years, sustainable evaluation of the energy system has attracted great attention [2, 9, 16]. Many different types of the energy system have been evaluated, such as hydrogen energy systems[1, 19], solar thermal power plants [3], wind energy [6, 10], electricity generation systems [7], nuclear energy [17], and energy systems for methanol production [18]. The energy system is a very complex system , which includes a series of processes such as production, sales, transportation, storage, conversion, transmission, and distribution. Its ultimate goal is to meet the terminal energy consumption demand to the maximum extent. The flow quantity, flow direction, state change of various energy varieties in the system, as well as the performance characteristics and operation status of production and transportation equipment will eventually affect the final energy supply. To clarify the relationship between primary energy supply and terminal energy consumption, it is necessary to analyze the energy flow process systematically. The energy system network diagram is a network flowchart that describes the quantity, flow direction, and state of energy materials in the energy system. It can reflect the characteristics and changes of the energy supply process in different stages, such as supply, reserve, production, transformation, and distribution. It is a useful tool for energy supply research.

However, most of the current studies focus on the evaluation of the energy system at the micro-level, which is a specific kind of energy type (e.g., hydrogen energy systems and electricity generation systems), with the energy system at the macro level missing. This neglect will set a barrier for the policymakers to better understand the

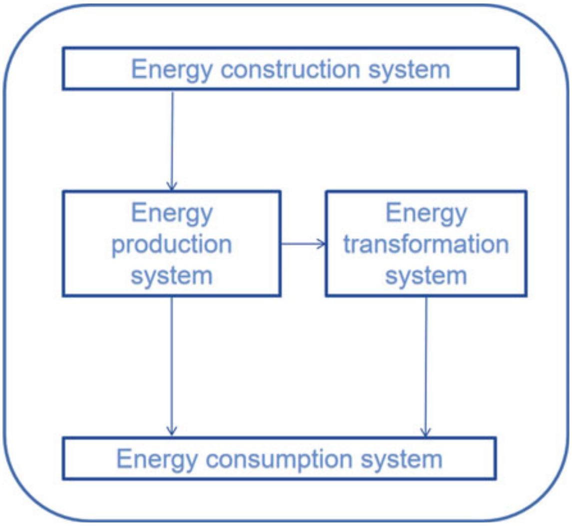


Fig. 1 Illustration of the whole energy system

overall situation of the energy system. To fill this gap, this study firstly constructed a framework of the energy systems, as shown in Fig. 1. According to the overall characteristics of China's energy flow between the front end and terminal, this study divides the whole energy system into the integration of four important sub-systems, which are energy construction system, energy production system, energy transformation system, and energy consumption system. 15 criteria are then selected to evaluate the sustainability of the energy systems of 30 provinces in China from 2013 to 2017 based on the best-worst method. Lastly, to further analyze the energy system structure type of each province, this study used the Q-type cluster method to group the 30 provinces into three categories. Some targeted policy implications are then proposed based on the sustainability evaluation results as well as the classification results.

2 Methodology and Data

This section includes two parts. The first part, sustainability assessment, will discuss the best–worst method used to evaluate the sustainability of the energy system of provinces, as shown in Sect. 2.1. The second part, cluster analysis, will introduce the Q-type cluster method, which can show the energy system structure types of each province, as shown in Sect. 2.2.

2.1 Sustainability Assessment

Following Rezaei [21], this study used the best-worst method to obtain the weight of each indicator. Compared to some other multi-criteria decision-making (MCDM) methods, the best–worst method is a comparison-based MCDM method that compares the best/the worst criteria with other criteria. The best–worst method can generate reliable results with fewer data requirements [20]. As a result, in recent years, the best-worst method has been widely used by many authors in terms of MCDM in the fields of the supply chain, airline industry, research and development performance [4, 11, 23]. The steps of the best–worst method can be summarized as follows based on Refs. [20–22]:

Step 1: Select a range of decision criteria, which can be denoted as $\{C_1, C_2, C_3, \ldots, C_n\}$.

Step 2: Find the best and the worst criteria among all alternatives, which is determined by the decision-makers.

Sept 3: Determine the preference of the best criteria over the other alternatives. The preference is expressed as a score ranging from one to nine. The score one indicates equal preference between the best criteria and an alternative. Score nine indicates the extreme preference of the best criterion over an alternative. These preferences can be expressed as a Best-to-Others vector, $A_B = (a_{B1}, a_{B2}, a_{B3}, \ldots, a_{Bn})$. a_{Bj} suggests the preference of the best criterion B over alternative j.

Step 4: Determine the preference of all alternatives over the worst criteria. The preference is also expressed as a score ranging from one to nine. These preferences can be expressed as Others-to-Worst, $A_w = (a_{1w}, a_{2w}, a_{3w}, \ldots, a_{nW})^T$. a_{jW} indicates the preference of alternative j over the worst criterion W.

Step 5: Calculate the optimal weights, $\left(w_1^*, w_2^*, w_3^*, \ldots, w_n^*\right)$. The solution to weight needs to satisfy some conditions, which are $w_{B/W_j} = a_{Bj}$ and $w_{j/W_W} = a_{jw}$ for all alternatives. As such, the maximum of $\left\{\left|w_B - a_{Bj}w_j\right|, \left|w_j - a_{jw}w_w\right|\right\}$ is needed to be minimized. The object function and constraints can be expressed as follows:

$$
\begin{aligned}
&\text{minmax}_j\left\{\left|w_B - a_{Bj}w_j\right|, \left|w_j - a_{jw}w_w\right|\right\}\\
&\text{s.t.} \sum_j w_j = 1\\
&w_j \geq 0, \text{for all} j
\end{aligned}
\tag{1}
$$

Since model (1) is not a linear problem, so it can be further transferred as follows:

$$\begin{aligned}
&\min \xi^{L} \\
&\text{s.t. } \left|w_B - a_{Bj} w_j\right| \le \xi^{L}, \text{ for all} j \\
&\left|w_j - a_{jw} w_w\right| \le \xi^{L}, \text{ for all} j \\
&\sum_j w_j = 1 \\
&w_j \ge 0, \text{ for all} j
\end{aligned} \tag{2}$$

By solving model (2), we can obtain the weight $\left(w_1^*, w_2^*, w_3^*, \ldots, w_n^*\right)$ and ξ^{L*}. ξ^{L*} is an indicator that can be used to measure the robustness of the solution. If ξ^{L*}gets closer to zero, the obtained weight will be more reliable.

In this study, the energy sub-systems are considered equally important, and therefore the weight of the energy construction system, production system, transformation system, and consumption system is set to be 0.25. Within each sub-system, the weight of the criteria is then set according to the best worst method mentioned above.

The criteria are then standardized based on an improved min–max method, which can avoid attaining zero value [27]. If the criteria are in positive dimension, the standardized criteria can be obtained as follows:

$$C_j^S = 0.9 \times \frac{x_{i,j} - \min_j(x_{i,j})}{\max_j(x_{i,j}) - \min_j\left(x_{i,j}\right)} + 0.1 \tag{3}$$

where C_j^S indicates the value of criteria j after standardization. For the criteria which are in negative dimension, the standardized criteria can be obtained as follows [27]:

$$C_j^S = 0.9 \times \frac{\max_j(x_{i,j}) - x_{i,j}}{\max_j(x_{i,j}) - \min_j\left(x_{i,j}\right)} + 0.1 \tag{4}$$

Based on the standardized criteria obtained above, we can then evaluate the sustainability of energy construction system, production system, transformation system, and consumption system as follows:

$$S_i = \sum_{j=1}^{J} w_j^* C_j^S, i = 1, 2, 3, 4 \tag{5}$$

where i indicate the energy sub-system.$i = 1$,$i = 2$, $i = 3$, and$i = 4$ mean energy construction system, energy production system, energy transformation system, and energy consumption system, respectively. J indicates the total number of the criteria in the corresponding energy sub-system. S_i ranges from 0 to 1. If S_i gets higher, it means the energy system is more sustainable.

The sustainable scores of the whole system can be obtained as follows:

$$S = \frac{1}{4}\sum_{i=1}^{4} S_i \tag{6}$$

where S indicates the sustainable score of the whole energy system and is ranging from 0 to 1. If S gets higher, it means the energy system is more sustainable.

2.2 Cluster Analysis

The scientific evaluation and ranking of the energy system are to evaluate the energy system of China's provinces quantiatively, and it is necessary to further analyze the energy system structure type of each province. In this section, cluster analysis was further used to cluster 30 provinces based on the 15 criteria. This study used Q-type cluster analysis, a type of hierarchical cluster method, to cluster the provinces into three types. The specific analysis steps are as follows [8]:

Step 1: Each observation is treated as a separate cluster. Identify the two clusters that are closest together based on the distance metric.
Step 2: Merge the two most similar clusters.
Sept 3: This iterative process continues until only a single cluster remains.

After finished the above process, a dendrogram can be obtained, which demonstrates the hierarchical relationship among the clusters. Strategies for hierarchical clustering generally fall into two types:

(1) Agglomerative: This is a 'bottom-up' approach. Each observation starts in its cluster, and pairs of clusters are merged as one moves up the hierarchy
(2) Divisive: This is a 'top-down' approach. All observations start in one cluster, and splits are performed recursively as one moves down the hierarchy.

This study chose the agglomerative type to do the cluster analysis. All criteria are standardized between 0 and 1 using the improved min–max method [27], which is then multiplied by the weight obtained using best–worst method. Euclidean distance is used as the metric for hierarchical clustering, as follows:

$$\text{distance} = \sqrt{\sum_i (a_i - b_i)^2} \tag{7}$$

2.3 Data Collection

This study used 15 criteria to measure the sustainability of the energy system of 30 provinces between 2013 and 2017. These data are mainly sourced from China Energy Statistical Yearbook, China Statistical Yearbook, and provincial statistical yearbooks. CO_2 emissions and energy consumption data are sourced from China Emission Accounts and Datasets. 'Transformation efficiency of electricity', 'transformation efficiency of heat', and 'transformation efficiency of coke and petroleum products' are calculated based on the energy balance table of each province. The efficiency of energy transformation refers to the ratio between the quantity of various energy products produced and the quantity of various energy inputs during the transformation process. In the energy balance table, all types of energy are firstly converted to standard coal and then used to calculate the transformation efficiency. 'Energy structure' indicates the share of coal consumption in total energy consumption. 'Energy intensity' indicates total energy consumption divided by GDP. Similarly, 'CO_2 emission intensity' and SO_2 emission intensity' can be obtained. 'Energy dependence' means the share of energy consumption in energy production, while 'electricity dependence' indicates the share of electricity consumption in electricity production. Energy consumption elasticity is energy consumption divided by GDP, while electricity elasticity equals to electricity consumption divided by GDP. GDP is converted to 2013 constant price based on the GDP index. GDP index is collected from provincial statistical yearbooks.

3 Results

This study assessed the sustainability of energy systems of 30 provinces of China. Section 3.1 first shows the 15 criteria selected to measure sustainability of energy construction system, energy production system, energy transformation system, and energy consumption system. The sustainability of both sub-system and whole systems of 30 provinces are measured based on best–worst method, as shown in Sect. 3.2. Last, Sect. 3.3 shows the cluster results of these 30 provinces and investigates their structure of energy systems.

3.1 Criteria Selection

Table 1 shows the four main components, 15 criteria, and these criteria's weight of the energy system. The weight is obtained based on the best–worst method mentioned in Sect. 2.1. A good comprehensive evaluation system should follow several principles when selecting criteria. The first one is a systematic principle. The evaluation index system has enough coverage to reflect the overall picture as well as sub-systems'

Table 1 Components and criteria of the energy system

Components	Criteria	Unit	Weight
Energy construction system	The share of investment in the energy industry in GDP	%	0.54
	The share of scientific research expenditure in GDP	%	0.29
	The share of investment in the treatment of industrial pollution in GDP	%	0.17
Energy production system	The share of electricity generated by nuclear, wind, solar, and hydropower in total electricity	%	0.14
	Energy dependence	–	0.29
	Electricity dependence	–	0.29
	CO_2 emission intensity	Tonne/10,000 Yuan	0.14
	SO_2 emission intensity	Tonne/10,000 Yuan	0.14
Energy transformation system	Transformation efficiency of electricity	%	0.54
	Transformation efficiency of heat	%	0.29
	Transformation efficiency of coke and petroleum products	%	0.17
Energy consumption system	Electricity consumption per capita	10,000 kWh/capita	0.17
	Energy consumption per capita	Tce/capita	0.26
	Energy intensity	Tce/10,000 Yuan	0.47
	The share of coal in total energy consumption	%	0.10

situation systematically, comprehensively, and truly in terms of sustainability. The second one is the scientific principle. According to the characteristics of the regional energy system, we should select the criteria with the most sustainable essence from all relevant factors and maintain the relative independence and balance of the selected criteria. The third one is a feasible principle. At present, China's energy-related data is not very detailed, so the availability of data should be considered when selecting indicators. The last one is the directive principle. The construction of the sustainable development of the energy system is a dynamic and complex process, which will continue to advance with the development of society, economy, science, and technology. The design of the criteria system must adapt to the current situation and trend of international science and technology development. Therefore, the criteria system should not only reflect the current sustainable situation of the energy system in the region but also make adjustments according to the domestic and international situation and environmental changes. Based on these four principles, this study selects three, five, three, and four criteria of the energy construction system, energy production system, energy transformation system, and energy consumption system, respectively.

For energy construction system, this study used three indicators to measure the conditions of the construction system, including ‘the share of investment in the energy industry in GDP’, ‘the share of scientific research expenditure in GDP’, and ‘the share of investment completed in the treatment of industrial pollution in GDP’. These three indicators are used to evaluate the preliminary energy infrastructure investment, spending on scientific research and development to improve the energy infrastructure, and investment of terminal treatment of pollutants, respectively.

For an energy production system, this study used four indicators to measure the condition of the production system, including ‘the share of electricity generated by nuclear, wind, solar and hydropower in total electricity’, ‘energy dependence’, ‘electricity dependence’, ‘CO_2 emission intensity’, and ‘SO_2 emission intensity’. Considering that the amount of fossil resources is finite, policymakers should promote the development of renewable energy. Renewable energy resources include biomass, wind, solar energy, geothermal, and hydropower. Nuclear energy is also an energy source that can replace fossil fuel [26], which can be regarded as a kind of sustainable energy [26]. Therefore, this study chose ‘the share of electricity generated by nuclear, wind, solar, and hydropower in total electricity’ to indicate the sustainability of the production system. If a region relies heavily on imported energy and does not have its own and powerful energy production system, this region tends to be more fragile once there is an external shock. Therefore, this study used energy dependence and electricity dependence to measure a region’s ability to withstand the negative impact of external shocks. Accompanied with energy output, some undesirable outputs will also be generated during the production process such as CO_2 emission and SO_2 emissions. The more undesirable outputs, the less environmentally friendly of the production system. As such, we used CO_2 emission intensity and SO_2 emission intensity to measure the environmental impacts of the energy production systems.

For the energy transformation system, we used the efficiency of the energy transformation indicator to measure the current conditions of energy processing and conversion equipment, production technique, and management. In this study, three types of efficiency of energy transformation are examined, including the efficiency of power generation, efficiency of heating, efficiency of coking, and petroleum refinery.

For the energy consumption system, this study used four indicators to measure the conditions of consumption systems, including ‘electricity consumption per capita’, ‘energy consumption per capita’, ‘energy intensity’, and ‘the share of coal in total energy consumption’. The rapid development of the economy and society has tremendously stimulated the expansion of energy demand, and China has been the largest energy consumer. In 2018, the primary energy consumption of China reached 3273.5 million tonnes of oil equivalent, accounting for around 23.6% of world consumption (BP, 2019). This study used ‘electricity consumption per capita’ and ‘energy consumption per capita’ to reflect the consumption condition. ‘Energy intensity’ is used to reflect the energy inefficiency of an economic entity. High energy intensity indicates a high price or cost of converting energy into GDP. This study used ‘the share of coal in total energy consumption' to reflect the energy structure of the energy consumption system. If the coal share is high, it indicates this decision-making unit is over-dependent on coal and less sustainable.

3.2 Scores of the Sustainability of Energy Systems

Table 2 shows the sustainability assessment of energy systems from 2013 to 2017. The last row shows the average of the sustainable scores of the energy systems of 30 provinces. The average of the sustainable score experiences a decrease from 0.54 in 2013 to 0.51 in 2015 and then witnesses a slight increase to 0.54 in 2017. In 2013, the top five provinces with the most sustainable energy system are Beijing (0.67), Hunan (0.61), Sichuan (0.59), Anhui (0.59), and Guangdong (0.59), while the top five laggards are Liaoning (0.49), Guizhou (0.48), Shanxi (0.48), Inner Mongolia (0.45), and Ningxia (0.40). In 2017, the top five best performers are Beijing (0.70), Anhui (0.60), Sichuan (0.60), Guangdong (0.59), and Shaanxi (0.57), while the Liaoning (0.48), Xinjiang (0.48), Inner Mongolia (0.47), Shanxi (0.46), and Ningxia (0.42) performed the worst in terms of the sustainability of energy systems. In general, the sustainability of the energy system of China does not make much improvement, but fluctuates at a relatively stable level, ranging from 0.51 to 0.54. There is still much room to improve the sustainability of the whole energy system.

Table 3 shows the sustainability assessment of energy construction, energy production, energy transformation, and consumption systems in 2017. The level of scores is represented by the depth of green color. The higher the sustainable scores are, the greener the color will be. It can be observed that, in the energy transformation system, Beijing has a much high level of sustainability, while the sustainable levels of the rest of the provinces are far from enough. This indicates that the inequality in sustainability in energy transformation is pretty large and policy-makers should not only place more emphasis on the improvement of sustainability of the energy transformation system but reduce the inequality of transformation system by technology diffusion from Beijing. Note that the development of sustainable and renewable energy with innovative technologies can vigorously promote China's sustainable development of energy production system. China has made remarkable progress in terms of renewable energy development, especially after the PRC law of renewable energy came into effect in January 2006 (The Chinese government, 2006). It is suggested to further promote the production of sustainable and renewable energy, and further replace fossil fuel types, such as coal. The energy production system should keep on mitigating over-dependence on fossil fuels.

Based on Table 3, the results show that Ningxia (0.76) has the most sustainable energy construction system, while Chongqing (0.19) is the least sustainable in energy construction systems in 2017. As for the energy production system, Sichuan (0.94) was the best performer, while Shanghai (0.48) was the worst performer in 2017. As for the energy transformation system, Beijing (0.99) performed the best, whereas Guizhou performed the worst (0.13) in 2017. Regarding the energy consumption

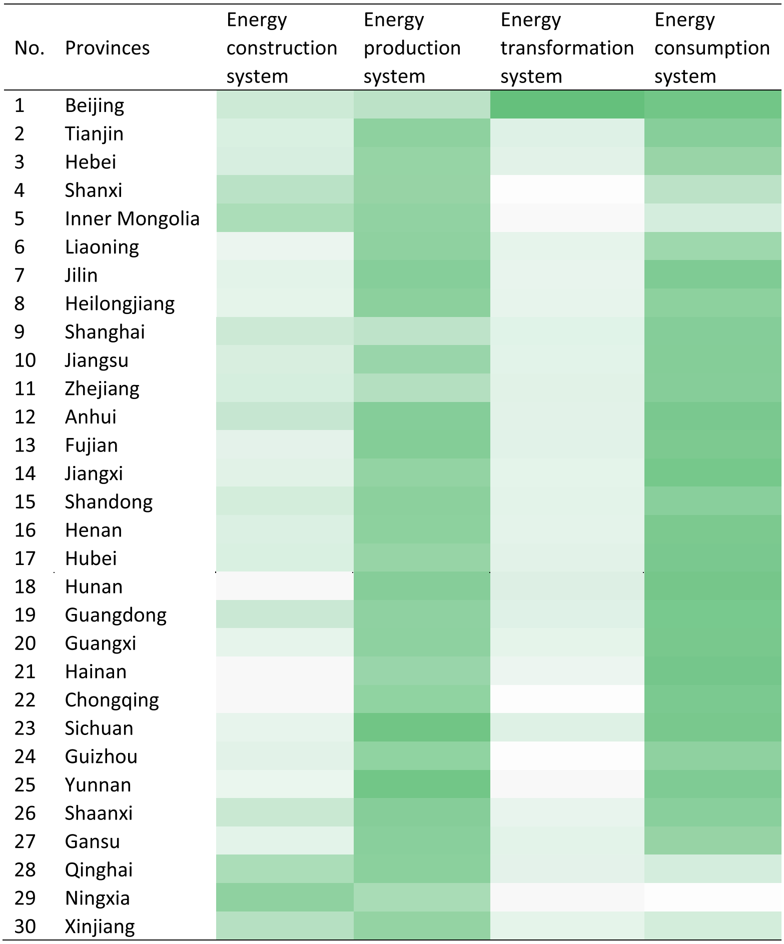
Table 2 Sustainability assessment of energy systems from 2013 to 2017

No	Provinces	2013	2014	2015	2016	2017
1	Beijing	0.67	0.68	0.67	0.68	0.70
2	Tianjin	0.56	0.52	0.53	0.53	0.55
3	Hebei	0.49	0.45	0.44	0.48	0.51
4	Shanxi	0.48	0.44	0.45	0.44	0.46
5	Inner Mongolia	0.45	0.43	0.41	0.42	0.47
6	Liaoning	0.49	0.46	0.45	0.45	0.48
7	Jilin	0.52	0.50	0.50	0.53	0.54
8	Heilongjiang	0.54	0.49	0.48	0.50	0.51
9	Shanghai	0.53	0.48	0.46	0.48	0.49
10	Jiangsu	0.55	0.51	0.51	0.51	0.53
11	Zhejiang	0.54	0.48	0.48	0.50	0.50
12	Anhui	0.59	0.55	0.54	0.60	0.60
13	Fujian	0.58	0.54	0.54	0.56	0.56
14	Jiangxi	0.56	0.52	0.52	0.54	0.55
15	Shandong	0.56	0.52	0.50	0.52	0.55
16	Henan	0.53	0.50	0.49	0.53	0.56
17	Hubei	0.57	0.54	0.53	0.55	0.55
18	Hunan	0.61	0.58	0.56	0.57	0.55
19	Guangdong	0.59	0.54	0.55	0.58	0.58
20	Guangxi	0.55	0.52	0.51	0.52	0.54
21	Hainan	0.58	0.54	0.50	0.50	0.50
22	Chongqing	0.53	0.50	0.49	0.49	0.48
23	Sichuan	0.59	0.58	0.57	0.60	0.59
24	Guizhou	0.48	0.47	0.48	0.47	0.48
25	Yunnan	0.55	0.53	0.55	0.53	0.55
26	Shaanxi	0.57	0.53	0.52	0.55	0.56
27	Gansu	0.57	0.55	0.52	0.53	0.51
28	Qinghai	0.50	0.45	0.44	0.48	0.50
29	Ningxia	0.40	0.39	0.40	0.43	0.42
30	Xinjiang	0.52	0.48	0.47	0.46	0.47
	Average	0.54	0.51	0.51	0.52	0.53

system, Beijing (0.93) performed the best in 2017, while Ningxia (0.12) was the worst performer.

For a better comparison between the situation between 2013 and 2017, Table 4 also demonstrates the sustainability assessment of energy construction, energy production, energy transformation, and consumption systems in 2013. Compared with the energy transformation system in 2017, the energy transformation system in

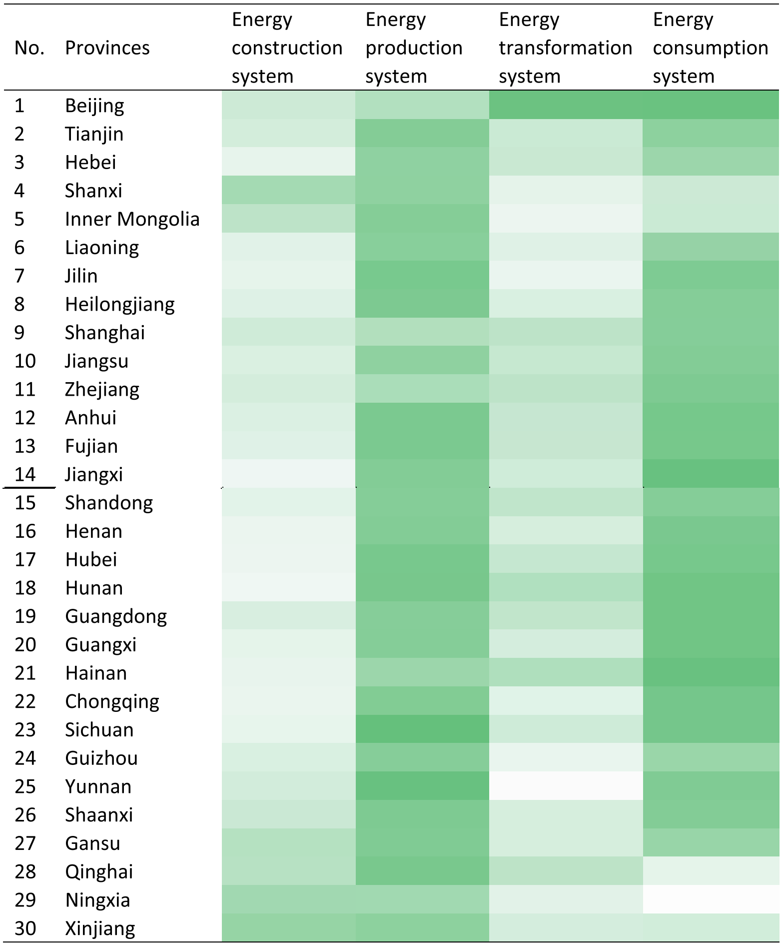
Table 3 Sustainability assessment of energy systems in 2017



No.	Provinces	Energy construction system	Energy production system	Energy transformation system	Energy consumption system
1	Beijing				
2	Tianjin				
3	Hebei				
4	Shanxi				
5	Inner Mongolia				
6	Liaoning				
7	Jilin				
8	Heilongjiang				
9	Shanghai				
10	Jiangsu				
11	Zhejiang				
12	Anhui				
13	Fujian				
14	Jiangxi				
15	Shandong				
16	Henan				
17	Hubei				
18	Hunan				
19	Guangdong				
20	Guangxi				
21	Hainan				
22	Chongqing				
23	Sichuan				
24	Guizhou				
25	Yunnan				
26	Shaanxi				
27	Gansu				
28	Qinghai				
29	Ningxia				
30	Xinjiang				

2013 has lower inequality in sustainability. This also indicates the technology gap among provinces has been enlarged in terms of the energy transformation system from 2013 to 2017. Beijing is still the best performer in the sustainability of the energy transformation system. Also, regarding the whole energy system, the energy system in 2017 is generally a little bit lower than the situation in 2013, indicating that the sustainability of the energy system has not improved.

Table 4 Sustainability assessment of energy systems in 2013

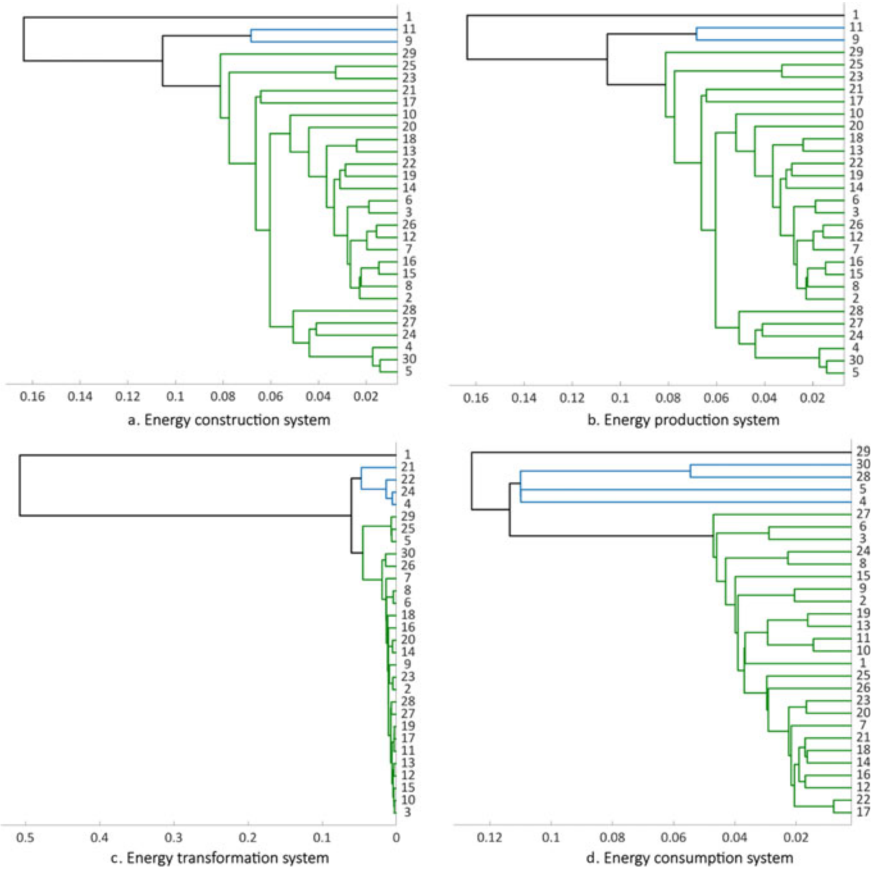


No.	Provinces	Energy construction system	Energy production system	Energy transformation system	Energy consumption system
1	Beijing	🟩	🟩	🟩	🟩
2	Tianjin	🟩	🟩	🟩	🟩
3	Hebei	🟩	🟩	🟩	🟩
4	Shanxi	🟩	🟩	🟩	🟩
5	Inner Mongolia	🟩	🟩	🟩	🟩
6	Liaoning	🟩	🟩	🟩	🟩
7	Jilin	🟩	🟩	🟩	🟩
8	Heilongjiang	🟩	🟩	🟩	🟩
9	Shanghai	🟩	🟩	🟩	🟩
10	Jiangsu	🟩	🟩	🟩	🟩
11	Zhejiang	🟩	🟩	🟩	🟩
12	Anhui	🟩	🟩	🟩	🟩
13	Fujian	🟩	🟩	🟩	🟩
14	Jiangxi	🟩	🟩	🟩	🟩
15	Shandong	🟩	🟩	🟩	🟩
16	Henan	🟩	🟩	🟩	🟩
17	Hubei	🟩	🟩	🟩	🟩
18	Hunan	🟩	🟩	🟩	🟩
19	Guangdong	🟩	🟩	🟩	🟩
20	Guangxi	🟩	🟩	🟩	🟩
21	Hainan	🟩	🟩	🟩	🟩
22	Chongqing	🟩	🟩	🟩	🟩
23	Sichuan	🟩	🟩	🟩	🟩
24	Guizhou	🟩	🟩	🟩	🟩
25	Yunnan	🟩	🟩	🟩	🟩
26	Shaanxi	🟩	🟩	🟩	🟩
27	Gansu	🟩	🟩	🟩	🟩
28	Qinghai	🟩	🟩	🟩	🟩
29	Ningxia	🟩	🟩	🟩	🟩
30	Xinjiang	🟩	🟩	🟩	🟩

3.3 *Cluster Analysis*

The results of hierarchical clustering are usually presented in a dendrogram. The cluster results of the whole energy system in 2017 can be found in Fig. 3. Chinese 30 provinces are categorized into three groups. The first group has the best energy system, containing only one province, which is Beijing. The second group has a generally good system, containing 24 provinces. The energy system of the third group performs the worst, containing five provinces (Hunan, Inner Mongolia, Qinghai, Ningxia, and Xinjiang). The cluster results of the four sub-systems in 2017 are shown in Fig. 2.

This study also shows the group categorization results from 2013 to 2017 in Table 5. Beijing is always in the first group, which indicates that Beijing performs



a. Energy construction system

b. Energy production system

c. Energy transformation system

d. Energy consumption system

Fig. 2 Dendrogram of four energy sub-systems of Chinese 30 provinces in 2017

the best in sustainable energy systems from 2013 to 2017. As for the third group, Qinghai is the worst performer, however, it changes to group two after 2014. During 2014–2016, Shanxi, Inner Mongolia, Qinghai, Ningxia, and Xinjiang are the worst performers within these three years. To be noticed, the province's classification in 2013, 2014, and 2016 are the same. In 2017, the group classification change to some extent. Hunan, Inner Mongolia, Qinghai, Ningxia, Xinjiang become laggardsin the sustainable energy system. It can be interpreted some of these provinces are abundant in energy resources and are manufacturing-based provinces. The relatively low value-added and energy-intensive industry could damage the sustainability of the energy system.

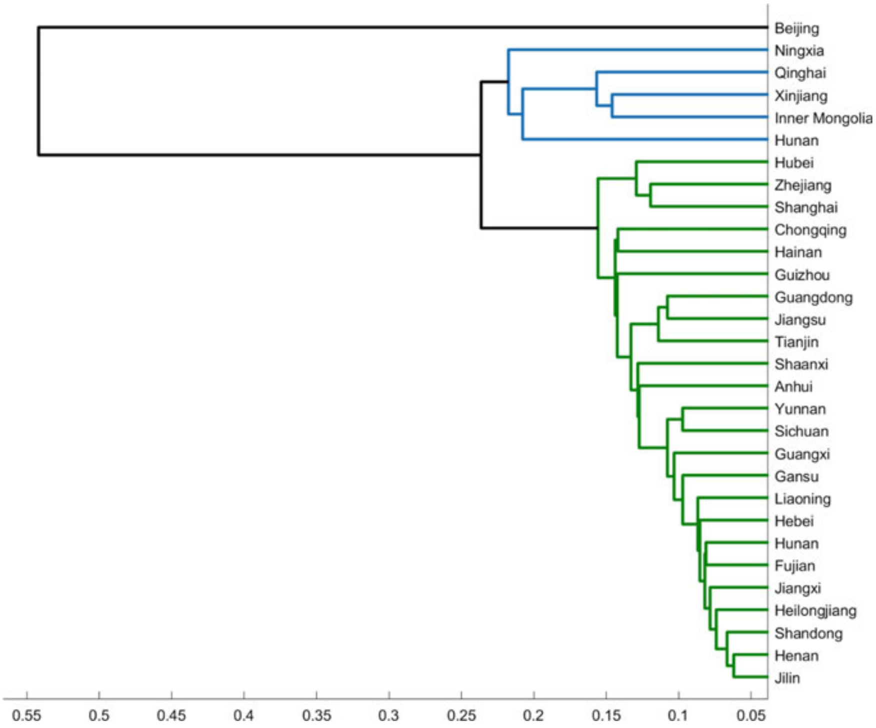


Fig. 3 Dendrogram of the energy system of the Chinese 30 provinces in 2017

4 Conclusions and Policy Implications

One of the most significant concerns of a society is making decisions, especially on sustainable development issues. Energy is one of the most basic needs of each society regarding resident consumption and production activities and has a key role in economic development. It is expected that the role of energy in economies and industries will increase in the forthcoming years. This study constructed a comprehensive energy system framework including energy construction system, energy production system, energy transformation system, and energy consumption system. Based on this system framework, we analyzed the sustainable situation of these four sub-systems of 30 provinces from 2013 to 2017. These 30 provinces were then categorized into three groups based on the Q-type cluster method, which can help us to better propose specific policies. The main findings are as follows:

First, the sustainability of the whole energy system still has much improvement in space. The average score of sustainability was 0.53 in 2017, which was lower than the average score in 2013 (0.54). Therefore, the sustainability of the energy system of China has not made much improvement, but fluctuates at a relatively stable level,

Table 5 Cluster division of 30 provinces

Group	2013	2014	2015	2016	2017
Group one	Beijing	Beijing	Beijing	Beijing	Beijing
Group two	Shanxi, Inner Mongolia, Ningxia, Xinjiang, Hunan, Tianjin, Hebei, Liaoning, Jilin, Heilongjiang, Shanghai, Jiangsu, Zhejiang, Anhui, Fujian, Jiangxi, Shandong, Henan, Hubei, Guangdong, Guangxi, Hainan, Chongqing, Sichuan, Guizhou, Yunnan, Shaanxi, Gansu	Hunan, Tianjin, Hebei, Liaoning, Jilin, Heilongjiang, Shanghai, Jiangsu, Zhejiang, Anhui, Fujian, Jiangxi, Shandong, Henan, Hubei, Guangdong, Guangxi, Hainan, Chongqing, Sichuan, Guizhou, Yunnan, Shaanxi, Gansu	Hunan, Tianjin, Hebei, Liaoning, Jilin, Heilongjiang, Shanghai, Jiangsu, Zhejiang, Anhui, Fujian, Jiangxi, Shandong, Henan, Hubei, Guangdong, Guangxi, Hainan, Chongqing, Sichuan, Guizhou, Yunnan, Shaanxi, Gansu	Hunan, Tianjin, Hebei, Liaoning, Jilin, Heilongjiang, Shanghai, Jiangsu, Zhejiang, Anhui, Fujian, Jiangxi, Shandong, Henan, Hubei, Guangdong, Guangxi, Hainan, Chongqing, Sichuan, Guizhou, Yunnan, Shaanxi, Gansu	Tianjin, Hebei, Shanxi, Liaoning, Jilin, Heilongjiang, Shanghai, Jiangsu, Zhejiang, Anhui, Fujian, Jiangxi, Shandong, Henan, Hubei, Guangdong, Guangxi, Hainan, Chongqing, Sichuan, Guizhou, Yunnan, Shaanxi, Gansu
Group three	Qinghai	Shanxi, Inner Mongolia, Qinghai, Ningxia, Xinjiang	Shanxi, Inner Mongolia, Qinghai, Ningxia, Xinjiang	Shanxi, Inner Mongolia, Qinghai, Ningxia, Xinjiang	Hunan, Inner Mongolia, Qinghai, Ningxia, Xinjiang

ranging from 0.51 to 0.54. Beijing (0.70) is the best performer of the whole energy system in 2017, while Ningxia (0.42) is the worst performer.

Second, there is great inequality in the energy transformation system. Beijing has a much high level of sustainability in the transformation system, while the sustainable level of the rest of the provinces are far from enough. This indicates that the inequality in sustainability in energy transformation is pretty large and policymakers should not only place more emphasis on the improvement of sustainability of the energy transformation system but reduce the inequality of transformation system by technology diffusion from Beijing. By doing so, it could significantly help to improve the sustainability of the whole energy system.

Lastly, based on the evaluation result and the clustering result, Beijing always belongs to group one and has a relatively more sustainable energy system. However, Shanxi, Hunan, Inner Mongolia, Qinghai, Ningxia, and Xinjiang have similar patterns of low sustainability of energy systems. It can be interpreted some of these provinces are abundant in energy resources and are manufacturing-based provinces. The relatively low value-added and energy-intensive industry could damage the sustainability of the energy system.

Based on the above empirical results, this study proposed some policy implications. First, Beijing should shoulder more responsibility to establish a technology diffusion system to improve the sustainability of other provinces, especially in terms of the energy transformation system. Second, the sustainability assessment results of the four sub-systems differ significantly and policies should be carried out based on the situation of each sub-system, which can help to bring up the sustainability of the whole energy system effectively. Lastly, policymakers should focus more on the energy-intensive provinces, which generally have a lower level of sustainability, such as Shanxi, Hunan, Inner Mongolia, Qinghai, Ningxia, and Xinjiang.

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Sustainable Energy System in the Archipelagic Country: Challenges and Opportunities

Ahmad Syauqi, Yoga Wienda Pratama, and Widodo Wahyu Purwanto

Abstract Archipelagic countries possess unique challenges compared to the continental ones. This chapter aims to review the current status of sustainable energy system analysis in archipelagic countries and to identify the key challenges and opportunities for developing sustainable energy systems. It is found that the framework of energy system analysis can be categorized into centralized, decentralized, and hybrid energy systems. Renewable energy penetration has better performance assessed by the sustainability index, especially on the economy, job creation, energy access, and reduce a country's CO_2 emission. Furthermore, the main barriers of energy system modeling and design are technical, socioeconomic, and political aspects, while its abundant renewable energy sources, declining cost of renewable energy and storage, and the archipelago's characteristics are key opportunities for further development. Finally, policy analysis for sustainable energy system deployment is discussed in the latter part of this chapter.

Keywords Sustainable energy · Sustainability · Energy system analysis · Archipelago · Island

1 Introduction

An archipelago is an area that consists of a group of islands. Archipelagos often consisted of several main islands and small or even remote islands. Because of the scattered land locations, archipelagos have different challenges in comparison to the continental country in all sectors with no exception in the energy sector. Table 1 shows lists of archipelagic countries with their corresponding energy status. Those differences include distributed energy generation, high cost of energy generation and transmission, scattered energy demand, isolated grid, high disparity among the islands, and often facing numerous natural disaster that threatens the integrity of the energy infrastructure.

A. Syauqi · Y. W. Pratama · W. W. Purwanto (✉)
Sustainable Energy Systems and Policy Research Cluster, Chemical Engineering Department, Faculty of Engineering, Universitas Indonesia, Depok 16424, Indonesia
e-mail: widodo@che.ui.ac.id

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Table 1 List of archipelagic countries and its energy status

Country	Area (thousand km^2) [1]	2019 population (million people) [2]	2019 GDP per capita (2010 USD/capita) [3]	Location	Main energy source in electricity mix [4]	2019 Share of renewables in electricity Mix [4] (%)	Renewable energy target	
							Year	Share (%)
Large Archipelago								
Indonesia	1904.5	267.6	4450.7	Southeast Asia	Coal	12.6	2025	23
Japan	377.9	126.3	49,187.8	East Asia	Natural Gas	26.3	2030	24
Philippines	300	108.3	3337.7	Southeast Asia	Coal	24.6	2025	23
New Zealand	268.6	4.69	38,992.9	Oceania	Hydro	83	2025	90
United Kingdom	244.8	65.6	43,688.4	Europe	Natural Gas	35.4	2020	20
Small Islands Developing States (SIDS)								
Cuba	109.2	11.2	6816.9	Caribbean	Oil	3.7	2030	24
Solomon Islands	28.4	0.67	1484	Oceania	Oil	8	2020	20
Fiji	18.3	0.92	4811	Oceania	Hydro	59	2020	81
Bahamas	13.8	0.39	27,477.9	Caribbean	Oil	0	2030	30
Vanuatu	12.2	0.3	2874.6	Oceania	Oil	12.6	2020	65
Trinidad & Tobago	5.13	1.3	15,105.1	Caribbean	Natural Gas	0	2021	10
Cape Verde	4.03	0.54	3907.6	West Africa	Oil	17	2025	100
Samoa	2.83	0.19	3860	Oceania	Oil	40	2016	10
Comoros	2.23	0.87	1409	East Africa	Oil	0	2030	43
Mauritius	2.04	1.26	10,949.2	East Africa	Coal	20.9	2025	35
Kiribati	0.81	0.11	1790.48	Oceania	Oil	17	2025	23

(continued)

Table 1 (continued)

Country	Area (thousand km^2) [1]	2019 population (million people) [2]	2019 GDP per capita (2010 USD/capita) [3]	Location	Main energy source in electricity mix [4]	2019 Share of renewables in electricity Mix [4] (%)	Renewable energy target	
							Year	Share (%)
Bahrain	0.75	1.44	20,913.1	Middle East	Natural gas	0	2030	5
Tonga	0.74	0.1	4054.9	Oceania	Oil	0.4	2020	50
Federated States of Micronesia	0.7	0.54	2728.6	Oceania	Oil	4.3	2020	30
Palau	0.45	0.02	12,260.2	Oceania	Oil	0.6	2020	20
Seychelles	0.45	0.98	14,962.4	East Africa	Oil	2	2030	15
Saint Vincent and the Grenadines	0.38	0.11	7503.5	Caribbean	Oil	19	2020	60
Maldives	0.29	0.53	8209.4	South Asia	Oil	4	2017	16
Marshall Islands	0.18	0.05	3066.9	Oceania	Oil	0.1	2020	20
Tuvalu	0.02	0.01	3943.4	Oceania	Oil	23	2020	100

Sustainable development, according to the United Nations' Brundtland Commission of 1987 [5], is the ability of systems to meet the needs of current society without affecting the ability of future generations to meet their needs. In agreement with this definition, sustainable energy is the energy that can meet the needs of the current generations and maintains the ability of future generations to meet theirs. Sustainable energy requires a balance between economic, social, and environmental aspects [6]. It covers sustainable energy systems, which are based on three core dimensions: economically viable, socially equitable, and environmentally acceptable. Currently, we are producing and consuming energy resources unsustainably, neither in developed nor in developing countries. Accordingly, sustainable energy transitions, especially for the archipelagic countries, require deeper organizational analysis for the transition's strategies. Hence, advancing a system-based analytical approach is required due to the limitations of the current energy systems modeling technique to deal with the long-term evolution of technologies, environment, social, and economic structures involved in the system. The system-based approach of sustainable energy systems identifies at least four layers. Those layers are the physical energy system that interacts with the other three layers, i.e., the socio-enviro-economic aspects that are commonly called sustainability. All those layers are exposed to the policy framework as presented in Fig. 1.

In recent years, sustainable energy systems from different perspectives have been reviewed. Renewable energy system concept in islands has been reviewed by Kuang et al. [7]. Prasad et al. [8] reviewed the potential, development status, challenges, and strategies for developing sustainable energy systems in islands. For grid design,

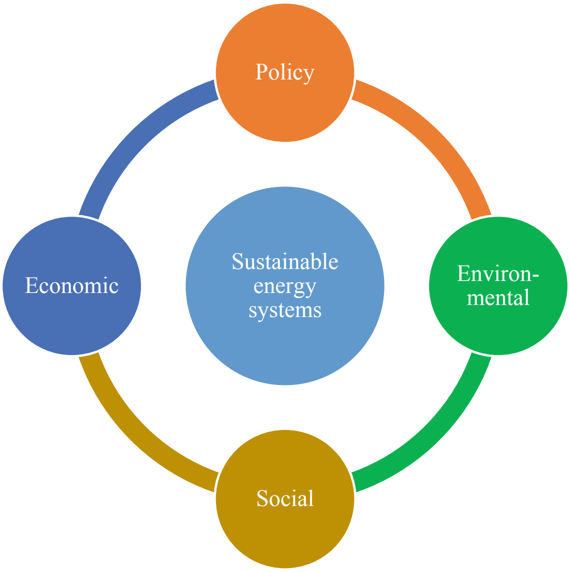

Fig. 1 Four structures of sustainable energy system

Mandelli [9] reviewed the use of off-grid systems in rural areas. A smart grid electricity system has also been reviewed by Philion [10]. In terms of sustainable indicators, Liu [11] has provided a review on the topic. Iddrisu and Bhattacharyya [12] developed a sustainability indicator namely the sustainable energy development index and compare the indicator with several existing sustainable indicators. Erahman et al. [13] has compared the energy security of Indonesia and other seventy countries. Purwanto and Afifah [14] assessed the impact of the socioeconomic factor on the sustainability of micro-hydropower plants. Reviews on policy to support sustainable energy systems development in Ghana has been conducted by Sakah et al. [15]. Lately et al. [16] carried out a review of the role of policymaking to develop sustainable energy systems, emphasizing the significance of policymaking towards energy transition.

This chapter aims to review the current status of the sustainable energy system analysis and sustainability in the archipelagic countries and discuss the key challenges and opportunities of sustainable energy system modeling. Finally, it enriched with a discussion on the policy analysis on sustainable energy system deployment.

2 Current Status of Sustainable Energy System Analysis for Archipelagic Nations

The energy system analysis focuses on assessing the current status of the system, grid interconnection among islands, and interaction between energy system with other sectors, and its sustainability in archipelagic nations.

2.1 Types of Energy System

The infrastructure energy of archipelagic nations is increasingly being recognized as not adaptive to a changing climate and uncertain future. Based on the literature review we identified 3 categories as follows.

2.1.1 Centralized Energy System

In a large archipelagic country with a large main island, it is reasonable to use a centralized energy network like in continental countries. Several large archipelagic countries have implemented the partition of a nation-wide system based on main islands/interconnected systems. For instance, Indonesia consists of 600 isolated grids and 8 major networks, i.e., Sumatra, Java and Bali, Kalimantan, Sulawesi, Maluku, Papua, East Nusa Tenggara, and West Nusa Tenggara. The Philippines has three main grids, i.e., Luzon, Visayas, and Mindanao. This partition follows the geographic condition of the country. Research on partitioned energy systems in the archipelago has been conducted with most of the studies model the system pivoting on the main islands, for instance [17–20]. These studies are similar to the energy systems planning done in the continental country in terms of grid connection. Although these researches bring enormous enlightenment on energy systems planning in the archipelagos, the unique challenges of archipelagic countries cannot be captured well in these researches.

Several studies investigated energy system design in islands with interconnection, and therefore, treated the system as centralized systems similar to that of continental countries, such as for the systems of Java-Madura-Bali (JAMALI) grid in Indonesia, Japan islands, and the United Kingdom. This type of interconnection is applicable even though using submarine HVDC cable due to the high demand and short distance between the island. Pratama and Dowell [21] investigated energy systems using the case studies of interconnecting island transmissions. However, the phenomena and the grid design that capture the characteristics of the large interisland grid are still poorly studied. Research on this type of grid is still limited and needs to be enhanced as the option to power grid an archipelago is not only a distributed energy generation, but also a centralized option.

2.1.2 Decentralized Energy System

For smaller islands like SIDS, the partition of large grids is infeasible to be applied, thus mini and off-grid connections become options. IRENA defined mini-grid as an integrated energy infrastructure based on distributed power generation [22], although mini-grid often operates as a stand-alone energy system, it also can be connected to the main grid. Off-grid can be defined as the operation mode of a mini-grid that is not connected with the main grid or also can be defined as a stand-alone power generation that can only supply one household or building [9, 22].

Many studies have been conducted to propose an energy system for remote islands [23–27]. These studies are conducted since remote islands are better suited for applying mini or off-grid systems as Segurado et al. [23] have done. They proposed renewable energy systems to supply two islands, Pico and Faial, with interconnected and non-interconnected scenarios. It is found that the levelized cost of electricity (LCOE) of the non-interconnected energy system is 15% cheaper than the interconnected one. Thus, off-grid electricity is a better suit for isolated islands. However, for groups of neighboring small islands, where energy demand is higher and the distance between islands is closer, interconnecting mini-grids are applicable as was demonstrated by Gils and Simon [28]. It is found that the use of sea cable connection can reduce energy generation cost up to 15%. Dorotic et al. [29] analyze the energy system design of small islands integrated with the main grid to allow import and/or export of electricity from/to the main grid. The integration is used to balance the intermittency of variable renewable energy (VRE) that is being implemented on the island. This intermittency is also addressed using sector coupling to store and supply another sector, i.e., transportation sector. Hence, the interconnection and sector coupling leads to a more reliable and secure supply on the island.

Regardless of the type of grid that is implemented, energy access in developing and remote islands often generates extra benefits from the non-energy sector such as enable clean water supply and develop the local economy. Mehrjedi [30] designs an independent energy system for an island that combines energy and clean water generation. The research found that hybrid solar-wind power with reversed osmosis desalination is the preferred option to fulfill electricity and water demand on an isolated island. Giudici et al. [31] propose an off-grid water-electricity system using a model to select the best strategy to minimize cost, water shortage, and electricity surplus. This research also emphasizes the use of dynamic optimization to optimize the size of an intermittent renewable energy power generator, particularly solar PV. It is found that using dynamic optimization, the system can be designed to be cheaper and more environmentally friendly. Fuad et al. [32] analyze the use of natural gas to generate electricity, water, and cooling load for fishery products. The implementation of the natural gas system supports reversed osmosis development that brings clean water into the remote island. The development of natural gas-refrigerator is also expected to boost the local economy. Salsabila et al. [33] designs a hybrid power generation system that generates electricity and also energizes the postharvest cocoa processing center in a community. The utilization of hybrid electricity to process cocoa can increase cocoa's selling price and boost the local economy.

2.1.3 Hybrid Energy System

While pivoting energy systems on the main islands and developing off-grid systems on the remote island are preferred options, both systems can be coupled to supplying energy in a large archipelago with a lot of smaller islands around the main islands. Bertheau and Cader [34] design an energy system that considers coupled decentralized and centralized systems with the option of submarine cable interconnections between islands. The result shows that it has more benefits to make most of the electrical systems a decentralized system than centralized. However, the research also suggests that the choice of using a centralized and decentralized system is influenced by electricity demand, distance, seabed contour, and submarine cable's investment cost.

The implementation of centralized, decentralized, or hybrid energy systems is a choice that depends heavily on the case. For the main island, a centralized system is a preferable option while for remote islands, a decentralized system is more suitable. On the other hand, a hybrid system is preferred for a large archipelago with some large islands and smaller and remote islands surrounding the bigger one. These categories of grid system are presented in Fig. 2. Thus, grid design in the archipelagic countries needs extensive planning and consideration where the spatial approach may become one option to allow more accurately represented system's characteristics in terms of the geographic location of the power generation system.

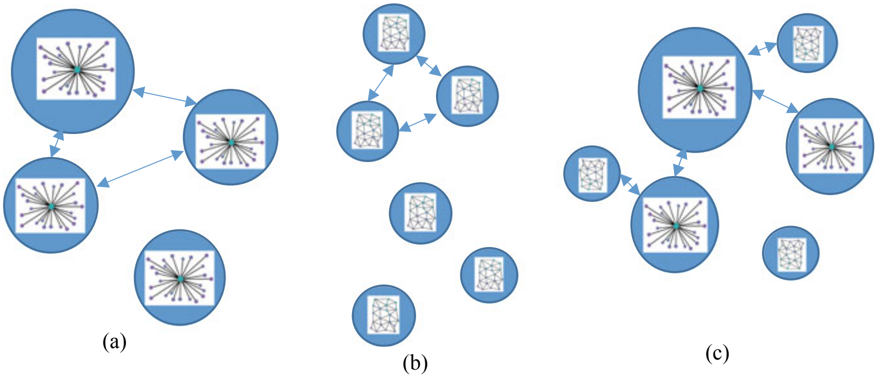

Fig. 2 Options of grid design in archipelagic countries **a** Centralized, **b** decentralized, **c** hybrid

2.2 Measuring Sustainability

To measure the effect on the future, the sustainability index is often used. While there are still numerous sustainability indexes with various aspects being developed, most of them share some common aspects, e.g., economic, environmental, and social, which are measured through various methods.

While optimization and simulation can become tools to design an energy system based on mentioned sustainability criteria, it cannot explicitly measure sustainability. Both tools only give limited aspects of sustainability, e.g., generation cost, greenhouse gas emissions, job creation, etc. Even though the result can predict the effect of the designed energy system on sustainability, they do not represent sustainability as a whole. Thus, a more holistic approach needed to be developed.

Measuring a system's sustainability involves numerous indicators, and therefore, aggregating those indicators into a simpler and more easily comprehend one is critical. To achieve this, weighting is one of the most common methods and is done by assigning a weight, normally 0–1, for each indicator that represents its importance to allow normalization of the set of selected indicators into the same range of number, e.g., 0–100 [11]. The weight assigned to each indicator can be uniform or vary, depending on the significance of each one. Researches have used this method to quantify sustainability, even some have become renowned indexes, such as the sustainable energy development index (SEDI) [12], energy development index (EDI) [35], and energy trilemma index (ETI) [36]. The analytical hierarchy process (AHP) is also a common method to measure sustainability. The method determines the relative importance of values of each pair of indicators in which values represent the relative preference of each pair-wise comparison [11]. This method has been used in several researches [37–39]. Another common method is principal components analysis (PCA) that is used in [13, 40]. PCA is a statistical approach to reduce the dimensionality of a data set that are interrelated [40]. This method can be a more advanced option than AHP or weighting methods. Another approach is the Fuzzy logic which does not only measure as true or false, but also vague data in a systematic way [41]. Fuzzy logic can also be combined with the AHP method to form Fuzzy-AHP (FAHP) method that is a more advanced approach [11]. Researches that have applied this method among others are [42–45].

The design of sustainable energy systems can be coupled with a sustainability index to measure the sustainability of the designed system. Research conducted by Pratama et al. [17] designed an energy system in Indonesia to minimize both the cost of the energy system and greenhouse gas emission using multi-objective optimization. Then, this study calculates the impact of designed sustainable energy systems on sustainability through three dimensions, i.e., economic, social, and environmental. The result shows that renewable energy penetration generates a positive impact on the economy. In terms of the social dimension, high renewable energy penetration gives the highest job creation which is in agreement with [46] that indicates renewable energy has a higher multiplier effect in this aspect. From an environmental perspective, renewable energy has a great role in reducing a country's emission. Zafeiratou et al. [47] proposed an energy system on an island with interconnected and non-connected scenarios. The proposed system then assessed using the trilemma index. The interconnected scenario and introduction of cleaner energy come out to have better performance assessed by the trilemma index. All the mentioned works are summarized in Table 2.

3 Key Challenges and Opportunities for Sustainable Energy System Modeling

Key challenges and opportunities for energy systems modeling and design are identified as follows:

3.1 Key Challenges

3.1.1 Technical Aspect

In the context of energy sustainability, the challenges come from the geographic aspect (spatial and regional interaction) of an archipelagic that spreads and is disconnected from each other. This characteristic makes energy accessibility becomes a serious problem with a low electrification ratio [48]. The fragmentation of lands makes it not feasible to supply electricity using a nationwide interconnected grid since it would be costly to use a submarine cable to exchange electricity among islands, especially to the remote ones [34]. Although the off-grid connection should be the answer, the existing preferred power generation still relies heavily on the diesel power plant. The dependency on diesel fuel also leads to higher logistic costs

Table 2 Research on Island energy system design and sustainability

Ref	Energy systems					Model type[a]	Sustainability aspects		
	Grid design	Electricity	Thermal	Sector coupling	Non-energy		Econ	Env	Soc
Pratama et al. [17]	Centralized	✓	✕	✕	✕	O	✓	✓	✓
Mondal et al. [18]	Centralized	✓	✕	✕	✕	O	✓	✓	✕
Purwanto et al. [19]	Centralized	✓	✕	✕	✕	O	✓	✓	✕
Esteban et al. [20]	Centralized	✓	✕	✕	✕	S	✕	✕	✕
Pratama and Mac Dowell [21]	Centralized	✓	✕	✕	✕	O	✓	✓	✕
Alves et al. [23]	Off-grid/Interconnected Mini-grid	✓	✓	✕	✕	S	✓	✕	✕
Kalamaras et al. [24]	Off-Grid	✓	✓	✕	✕	A	✓	✕	✕
Moretti et al. [25]	Off-grid	✓	✓	✕	✕	O	✓	✕	✕
Bertheau [26]	Off-grid	✓	✕	✕	✕	A	✓	✕	✕
Meschede et al. [27]	Off-Grid	✓	✕	✕	✕	A	✕	✕	✕
Gils and Simon [28]	Interconnected Mini-grid	✓	✓	✓	✓	O	✓	✕	✕

(continued)

Table 2 (continued)

Ref	Energy systems					Model type[a]	Sustainability aspects		
	Grid design	Electricity	Thermal	Sector coupling	Non-energy		Econ	Env	Soc
Dorotić et al. [29]	Mini-grid	✓	✓	✓	×	S	✓	×	×
Mehrjerdi [30]	Off-grid	✓	×	×	✓	O	✓	×	×
Giudici et al. [31]	Off-grid	✓	×	×	✓	O	✓	✓	×
Fuad et al. [32]	Off-grid	✓	✓	×	✓	S	✓	×	×
Salsabila et al. [33]	Off-grid	✓	×	×	✓	O	✓	×	×
Bertheau and Cader [34]	Centralized & Decentralized	✓	×	×	×	O	✓	×	×
Zafeiratou and Spataru [47]	Off-grid/Interconnected Mini-grid	✓	×	×	×	O	✓	✓	✓

[a] O = Optimization, S = Simulation, A = Analysis

due to the fragmented land [49]. It creates a disparity problem among islands, thus the decision-making on grid-integration among island or stand-alone micro grid and off-grid is critical. This high level of disparity leads to many discrepancies in many sectors, e.g., prosperity, education, gender equality, and health [50–53], that should be addressed in the system.

The archipelagic countries are also frequently facing uncertainty that is caused by natural disasters and is vulnerable to the climate change effect. Many are located in the ring of fire, an area in the pacific rim where earthquakes and volcanic eruptions are often [54]. Another island group is also vulnerable to the hurricane with a higher hurricane category that happens more often that threat the energy infrastructure, such as wind power and resulting in higher cost to develop wind power facilities [55]. Another island group experience severe effect of climate change due to the effect of sea level rising and shift in rainfall, especially for islands located near the equator [56]. Thus, a complete understanding of the sustainable energy system in archipelagic countries reveals the essential role of uncertainty analysis.

Other aspects of challenges are sector coupling and increasing the temporal resolution of intermittent generation units based on variable renewable energy [57, 58].

3.1.2 Economic Aspect

The main barriers for developing a sustainable energy system in the island country, especially driven by RE deployment, are high initial investment mainly related to the small scale of the project and lack of access to the low cost of capital, small market size, and fossil fuel subsidies that make RE can't compete [59]. Some small and remote islands have an abundant international fund to finance the renewable energy project but most project fails due to limited allocation in capacity building and technical assistance to ensure the operation and maintenance of the project. Most of the projects are also prioritizing large-scale renewable energy power plant instead of off-grid power plant [49, 60] even though off-grid electricity is proven to be a better suit. Large-scale power plant is preferable to the politician and donor due to more attractive view.

Energy system modeling needs to focus on innovative policy intervention scenarios. The policy needs to be included in the planning as a scenario to study the impact of the policy on the designed system. For instance, the model can include a scenario that involves the implementation of feed-in-tariff (FiT) to study the impact of FiT to decarbonize the electricity system. Another crucial challenge is flexible loads due to supply and demand flexibility that will affect the economic aspect of energy price and production cost (LCOE).

3.1.3 Political Aspect

Political challenges are the most important barrier to address in implementing renewable energy policy. Blechinger [59] analyzes the Caribbean islands' sociopolitical condition to implement renewable energy and concludes that lack of regulatory framework and legislation for private investors are seen as the most important factor that threatens the implementation of renewable energy. Bertheau et al. [61] and Dutu [62] also agree with the previous research, that political challenges are among the most important factors to address. Both researches emphasize in streamline policy, strong regulatory framework, private sector involvement, and extra-political willingness are a must to support the implementation of renewable energy. Particularly in political willingness, some country's policies are seen unwilling to switch from carbon-intensive energy systems to cleaner ones. This can be seen from the subsidies of fossil energy and few incentives towards renewable.

Besides the political factor, the social aspect of the community needs to be considered too. Vandalism and lack of technical skills have damaged the sustainability of the project [49, 63]. Some researchers even argue that capacity building is the most essential factor in sustainable energy project, e.g., [49, 64, 65]. Thus, the project needs to be focused more on the human aspect rather than the infrastructure to ensure the continuity of the project.

3.2 *Key Opportunities*

3.2.1 Abundance of Renewable Energy Resources

Most archipelagic countries are gifted with renewable energy potential. Since agriculture is the backbone of the economy in many archipelagos, bioenergy potential is high. Solid biofuel has become the primary energy source for cooking in SIDS. Liquid biofuel can be applied to reduce oil consumption in the transportation sector. Biogas from livestock manure is also a promising energy source to substitute or decrease fuel consumption for a diesel power generator. Although it must be noted that small islands like Kiribati do not have enough bioenergy potential to supply the energy demand due to the limited land area. Solar energy has become one of the most progressive renewable energy for off-grid and on-grid electricity. Luckily, many of the countries are located near the equator where the potential of solar energy is high. With lots of international aid, a lot of households have now enjoyed the rooftop solar PV [49, 55]. Hydropower is potential energy source in some archipelago, for instance, Fiji is the only country in Oceania to generate electricity mainly from renewable thanks to abundant hydropower potential. Japan's hydropower is the primary source of renewable electricity and has become one of the leading countries in terms of installed capacity. In addition, with future energy systems demand for low-cost large-scale energy storage, hydropower emerges as one of the leading technologies. As previously mentioned, most archipelagos are located in the ring of fire where geothermal energy is abundant such as in Indonesia and the Philippines [66]. Ocean energy is a form of energy that can be harvested by many archipelagos especially the one located in Oceania [67].

3.2.2 The Declining Cost of VRE and Storage

The rapid cost reduction of renewables and energy storage should have been a strong opportunity for the islands to shift towards more sustainable energy. For instance, in 2010, the LCOE of PV power plant is more than \$0.37/kWh, in 2019, the cost has been declined to \$0.07/kWh. Wind energy has been experiencing a rapid cost reduction since 2010, where onshore and offshore wind cost has dropped by 39% and 30%, respectively [68]. Along with PV and wind power, many renewables are continued to be cheaper and become competitive with fossil. Energy storage technology has been experiencing a reduction in cost as well. Levelized cost of storage (LCOS) of battery especially lithium has been massive falling. Lithium battery's LCOS has been decreased by 35% since early 2018 [69]. This trend is unlikely to stop and it is estimated that the LCOS of lithium battery will decrease until below 100 USD/MWh in 2050 [70]. Economics of scale and the effect of learning drives both technologies to remain undergo fast cost reduction in the future [68, 70, 71]. This cost reduction leads to higher renewable energy penetration that has several impacts, e.g., higher job creation, welfare improvement, GDP improvement, and fewer health problems [46, 72, 73].

3.2.3 Endogenize the Archipelago Characteristics

The planning done in one country must consider the inherent social and cultural aspects of the respective country. The characteristics of a country need to be endogenized in the model to make better planning. Thus, the approach to develop an energy system can differ from one country to another. Although one planning approach can be applied in a country it does not mean it can be implemented in another country. For instance, the implementation of FiT. Indonesia and Philippines are neighboring countries that implement FiT in about the same year, but the result is quite different. After implementing FiT, Philippines can add 1381 MW of renewable electricity in just five years. While Indonesia, in the same period, can only add 36.8 MW [74]. The developed country approaches to implement energy transition also common to be forced in developing countries. Some transition theories and approaches may not applicable in developing countries. Those approaches are developed in a developed country and may not answer the site-specific challenges that do not appear in the developed countries [75]. Market liberalization is often mentioned in the energy system planning developed by advanced countries, but it may not suitable for the developing country which is still struggling with the energy access issues, especially in the rural areas [76]. Thus, the energy system planner must be aware of the uniqueness of the modeled country or area to design a suitable energy system. This type of planning approach is still limited, and thus it can be seen as opportunities for the planner to develop a more holistic energy system.

4 Policy Analysis

The archipelagos have set their target to a more sustainable energy future, driven by low energy security, low energy access, and vulnerability to climate change (see Table 1). Although these targets are translated into action, some island countries facing several barriers from geographical, financial, and sociopolitical aspects.

To overcome the aforementioned challenges and meet renewable energy targets, a strong science-based policy needs to be developed [77, 78]. In general, there are 3 characteristics that most successful countries share in common: a long-range goal-oriented vision, concrete policies, and measures to support the vision [79]. Before having these three, archipelagos still have things to be done. The most important one is the lack of political capacity in the regulating body. Lack of political capacity can be distinguished into two factors, i.e., lack of regulatory framework and lack of energy experts in governmental bodies [77, 80]. To address both, capacity building in the respective country's department of energy needs to be done by developing advanced knowledge for every employee in the institution. Neighborhood small island countries can also cooperate to establish a trans-national regulating body that focuses on developing knowledge and skill required to design a better energy policy framework.

Deployment of renewable energy not only requires strong political will but also a good financing scheme for private sector involvement. One of those is an auction which can lead to a rapid increase in renewable energy generation at a competitive price. Auction needs a massive amount of projects and a large pool of qualified bidders to be effective [81]. Otherwise, the auction will not have a significant impact on a country's renewable energy penetration. Indonesia and the Philippines are two of the largest archipelagic country and both have not met the criteria for gaining the benefit of implementing an auction [74]. Another scheme is FiT which can be a determining factor for renewable energy growth. To gaining the best impact of FiT archipelago, several key aspects lead to the success [82], which includes: provide reliable grid infrastructure and remove all barriers to grid connection, keep tariff at an attractive level that provides enough return of investment but do not add unnecessary burden to the end customer, a flexible policy that follows the cost reduction of renewables, policies must still in line with emission reduction vision that has already set, design a policy that is as simple as possible but accountable to keep administrative cost low, and raising public awareness of renewable energy and keep the cost as low as possible to end customer. As good as FiT can be, it cannot be implemented in low population islands where competition among power generation technologies is limited. Thus, the government can give a certain amount of quota for renewable energy to accelerate renewable energy growth in a highly fossil-subsidized environment. This quota can only become the step-stone of renewable and make renewable energy more competitive by creating incentives for renewable and reducing fossil subsidies. Blechinger and Goldammer [80] states that positive incentive toward renewable can be in kind of “fuel surcharge” where the price of renewables is a proportion of diesel price, e.g., 80%. Thus, it can reduce the retail price and boost social acceptance.

Some island countries encounter social barriers in the form of a lack of technical skill and vandalism. Thus, education on maintaining and operates renewable energy technology is a must. Anirudh [77] also argues that national and regional programs of capacity building are determining factors to implement renewable energy.

A strong science-driven policy requires data availability and validity . However, small developing islands tend to have scattered and incomprehensive data. Thus, it is hard to analyze, make plans, assess, and project the progress of renewable energy [83]. The data required include renewable energy potential map for each technology, historical power plant production, power plant installed capacity, historical energy consumption, and historical energy mix.

Finally, poster of the deployment of a sustainable energy system has positive effects on GDP and enables a wide range of socioeconomic benefits, and local economic value creation.

5 Conclusion

This chapter discusses the opportunities and challenges of sustainable energy systems development in archipelagic countries. For designing an energy system, the selection of grid designs is sensitive to the size of an archipelago. The choice of centralized, decentralized, or hybrid energy system is found to be case-specific. For larger systems, it is common to use the centralized network and for smaller ones, the use off-grid electricity can be a better option, and a hybrid system can be used for a large island with several smaller islands surrounding the large island. The use of submarine cable for interconnecting between systems is also case-sensitive. The decision of using it depends on the energy demand, the distance between the island, seabed contour, and cable investment cost.

It is found that archipelagic countries’ challenges and opportunities consists of several point. The challenged comprise of three aspects, technical, economic, and political aspects. The technical challenge covers the inherent barrier of geographic aspect on the archipelago. The economic challenge speaks about the high initial cost of renewable energy systems. While the political challenge comprises of the socio-political barriers that are often faced in the deployment of sustainable energy systems. These challenges must be captured well in the energy system analysis to give better planning results. The opportunities include of three aspects, abundant renewable energy resources, declining cost of VRE and energy storage, and endogenize the archipelago characteristics.

In the policy analysis section, policy options to be implemented in the archipelagos are also discussed. One of the key options is strengthening the regulatory framework and then followed by finding an appropriate financing scheme. Addressing social barriers through capacity building also appears to be an important factor. In addition, the importance of data as the basis to formulate the deployment strategy of the sustainable energy system are discussed as well.

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Elements of Holistic Sustainability Assessments for Energy Systems

Oludunsin Arodudu

Abstract This study highlights the relevance of energy to nature and society, elaborates on the significance of energy systems for the sustainability of human civilization, and spells out parameters for assessing the sustainability of energy systems, as well as how it ought to be measured to be considered holistic. This study also presented the fundamental elements and sub-elements of holistic sustainability assessment for energy systems at a glance (using the space, time, impact and stakeholder-STIS conceptual structure) and suggested its application as a conceptual frame for determining the data and information requirements of holistic sustainability assessment for energy systems. The STIS conceptual structure was adapted because it describes/lists the basic elements and sub-elements of holistic sustainability assessment frameworks. This study recommended the use of the STIS conceptual structure for evaluating the inadequacies of individual methodologies, as well as combinations of methodologies as tools for holistic sustainability assessment of energy systems. Consequently, it is also expected that the STIS conceptual structure be adopted as a systems-thinking or mind frame in determining the combinations of methodologies that will help fill identified methodological gaps, in order to provide complete information which is the goal of holistic sustainability assessments for energy systems. Finally, this study discussed the limitations of the energy systems of the future (mostly renewable energy systems) and offered recommendations for enhancing their sustainability in the long run. Based on the limitations identified and recommendations offered, this study further described the likely features of future holistic sustainability assessment frameworks for evaluating future energy systems.

O. Arodudu (✉)
Department of Geography, Maynooth University, County Kildare, Ireland
e-mail: oludunsinarodudu@gmail.com; dunsin.arodudu@mu.ie

International Centre for Systems Thinking, Integrative Knowledge and Sustainability in Africa, Lagos, Nigeria

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Abbreviations

AHP	Analytic hierarchy process-AHP
ANP	Analytic network process
CBA	Cost-benefit analysis
EIA	Environmental impact assessments
ELECTRE	Elimination and Choice expressing Reality
EROI	Energy return on energy investment
$\text{EROI}_{\text{distr}}$	Energy return on investment after distribution
EROI_{dm}	Energy return on investment of domestic energy supplies
EROI_{eco}	Energy return on investment of an economy
EROI_{ext}	Energy return on investment of extended use (same as use)
$\text{EROI}_{\text{farmgate}}$	Energy return on investment after farmgate (same as EROI_{std} for cultivation and harvesting of bioenergy feedstock)
EROI_{im}	Energy return on investment of imported energy supplies
$\text{EROI}_{\text{minemouth}}$	Energy return on investment after minemouth (same as EROI_{std} for extraction of fossil and mineral based raw materials for energy production)
EROI_{pou}	Energy return on investment at point of use (same as after refining/production)
$\text{EROI}_{\text{prod}}$	Energy return on investment after production (same as after refining)
EROI_{ref}	Energy return on investment after refining
EROI_{soc}	Energy return on investment of a society
EROI_{std}	Energy return on investment after resource extraction
$\text{EROI}_{\text{trans}}$	Energy return on investment after transmission or transportation (same as after distribution)
EROI_{use}	Energy return on investment of use
$\text{EROI}_{\text{waste source (landfill/dump site/bin)}}$	Energy return on investment after waste source/waste collection (same as EROI_{std} for collection of bioenergy feedstock from waste sources e.g. landfills, dump sites and bins)
GERR	Gross energy requirement ratio
GDP	Gross Domestic Product
GIS	Geographical Information Systems
HIA	Health impact assessment
LCA	Life cycle assessment
LCSA	Life cycle sustainability assessments

MAUT	Multi Attribute Utility Theory
NEG	Net energy gain
NER	Net energy ratio
OECD	Organization of Economic Co-operation and Development
PEF	Process engineered fuel
PROMETHEE	Preference ranking organization method for enrichment evaluation
RDF	Refuse derived fuel
SEA	Strategic environmental assessment
SIA	Sustainability impact assessment
SMCA	Spatial multi-criteria assessment
SA	Sustainability assessments
STIS	Space, time, impact and stakeholder
SRF	Solid recovered fuel

1 Introduction

Energy is central to the existence of life on earth and the universe as a whole [1, 2]. Nature recreates itself using energy from sun and the core of the earth [3–5]. Human civilizations are also products of discovery and use of new forms of energy [5, 6]. Both decline and growth in the population or size of different components of nature (i.e. water, plant, animal, soil/rock etc.) is often a result of activities of organisms with higher energy living on (i.e. deriving their energy from) or displacing (i.e. predating on) those with lower energy, or those dependent directly on the elements of the environment having enough energy and experiencing minimal disturbance needed for the derivation of the energy they need for survival and avoidance of extinction [3, 7]. Likewise, humans derive their energy for survival, sustenance, development and civilizations from exerting higher energy and control on the elements of their surrounding environments (e.g. biomass, soil, rock, water, wind, sun, air, etc.) and sometimes distant environments (through internal trade and imports) [4, 8]. Extinction of different species has often been as a result of disturbance by higher organisms and lack of capacity of such species to derive the energy they need to survive and continue to reproduce [2, 9]. Also, human civilizations and eras of economic boom either seized or evolved because the materials and energy sources that supports particular human cultures and ways of life at those points in history became scarce and unavailable or because new ones were discovered [7, 8]. Energy is therefore important for the continuous existence of life on the earth and the sustenance of human civilizations [10, 11].

Despite energy's centrality to life on earth and the universe (especially nature and humanity), it is neither created nor destroyed, it can only be converted from one form to another i.e. it is always conserved (First Law of thermodynamics) [7, 12]. The conversion of energy from one form to another for human use is usually not done in isolation but within the context of interrelated and interacting structures, entities or elements called energy systems [13, 14]. Energy systems may comprise of internal structures and boundaries, as well as surrounding (external) environments which exerts influence on it and otherwise [14, 15]. Energy systems evolve (in the case of nature) or are derived (in the case of humanity) for the purpose of supplying or producing the energy needed for the continuity of organism's life or human civilization (as the case may be) [3, 9]. The capacity of energy systems (either in nature or human society) to produce or obtain the energy or material resources they need for continued sustenance of their functions can be described as energy system's sustainability [7, 10]. Evaluating energy system's sustainability can be a laborious task because several elements and sub-elements of sustainability assessment need to be considered to have a holistic view of the sustainability of particular energy systems. Consequently, the objective of this study will be to uncover the elements and sub-elements of holistic sustainability assessments for energy systems using the Space, Time, Impact and Stakeholder (STIS) conceptual structure. In accordance with this objective, Sect. 2 examined the different transition phases of global energy systems and described the methods previously used for evaluating and ensuring their sustainability. Section 3 described how to measure the sustainability of energy systems, bearing in mind the fact that energy sufficiency is the principal determinant for energy system's sustainability. Section 4 highlighted the need for holistic sustainability assessments of energy systems, and presented the elements and sub-elements of holistic sustainability assessment of energy systems using the STIS conceptual structure. Section 5 enumerated the choices of methodologies and methodological frameworks available for sustainability assessment of energy systems and suggested the STIS conceptual structure as a mind frame for ensuring the delivery of complete information that guarantees that sustainability assessments of energy systems are entirely holistic in scope. Section 6 described the likely features of holistic sustainability assessment frameworks for evaluating future energy systems (expected to be dominated by renewables) based on identified limitations of such energy systems and sustainability pathways for overcoming the identified limitations.

2 Energy Systems and Sustainability

This section described the different transition phases of global energy systems and the methods previously employed for evaluating and ensuring sustainability.

Before the advent of modern energy systems, the use of energy systems by humans were limited to the use of wind mill, water-driven innovations, as well as human and animal labour for mechanical work, and the making of fire (chemical energy) for heating, lighting and warding off of predators [16, 17]. Energy systems in contemporary human societies are however further applied for operation of both light and heavy machineries, devices and appliances for domestic, industrial and commercial purposes, often at the expense of huge investments derived from fossils formed as a result of thousands or millions of years of geological activity [18, 19]. While the study of internal structures and boundaries of different energy systems led to the invention of modern energy systems, the study of the influence of surrounding environments, as well as changes in internal structures and boundaries helped improve them continuously [13, 15]. Subsequent proliferation of contemporary energy systems and increased awareness of their impacts on the environment led to significant public interest in formulation of better environmental protection and sustainability measures [20–22]. The realization of the short-term, as well as far reaching effects of the mostly fossil fuel based global energy systems on climatic systems and its attendant impact on human health, biodiversity and other sustainability aspects have become a major source of concern to both researchers and policymakers worldwide [21–24]. In these regards, achieving energy system's sustainability will involve minimizing or eliminating the negative impacts of energy systems on the one hand, and optimizing their positive benefits on the other hand (i.e. keeping the capacity of energy systems to sustain human civilization without harming nature) [20, 22]. In order to strike the needed delicate sustainability balance in the management of energy and other nature-human systems, (i.e. ensure harmony and/or perpetual co-existence between nature and human civilization) accurate information for informed decision making is a strong pre-requisite [23, 25]. Informed decisions on sustainability issues (energy systems inclusive) are a product of evidence-based information obtained via the use of theory, as well as practical (i.e. stakeholder) based tools, methodologies, protocols and frameworks [21, 24]. Different tools, methodologies, protocols and frameworks have been developed over the last six to seven decades for understanding, reducing or eliminating the adverse impacts, as well as maximizing the benefits of modern energy systems at different scales (local, regional or global) [22–25]. These include life cycle assessment (LCA) protocols, cost-benefit analysis (CBA), environmental impact assessments (EIA), health impact assessment (HIA), strategic environmental assessment (SEA), biodiversity impact assessment, social impact assessment, economic impact assessment, sustainability impact assessment (SIA), sustainability assessments, multi-criteria assessments, multi-criteria sustainability assessments/decision making and more recently life cycle sustainability assessments (LCSA) [24–26]. At the inception of studies quantifying the impacts and benefits of energy systems over space and time, the methodological focus was first (before 1950s) on reduction of economic cost (e.g. CBA etc.), and later (after 1950s) on the lessening or elimination environmental or health impacts (EIA, HIA etc.) [20, 26]. Subsequently, there was the need to include other individual impact categories (e.g. other environmental impacts like biodiversity) or whole impact dimensions/spheres (i.e. social and economic dimensions) in order to gain a holistic understanding of all impacts and benefits associated with particular energy systems [24, 27]. This led to the development of SEA, biodiversity impact assessment, social impact assessment, economic impact assessment etc. [20–22]. This was followed by emphasis on the importance of including the perspectives and preferences of stakeholders, in order to ensure sustainability and/or sustainable development i.e. the sustenance of the capacity of an environment, society or economy to produce and use energy without hampering the potential of future generations to do the same [23–27]. Examples of methodologies and frameworks for inclusion of stakeholder views into the design of energy systems included SIA, sustainability assessments, multi-criteria assessments, multi-criteria sustainability assessments/decision making and LCSA [20, 24]. LCSA do not only attempt to consider all impact categories and dimensions, as well as stakeholder's perspectives/preferences over space and time, it also tries to do so from a life cycle or value chain point of view [23, 27]. The inclusion of stakeholder's input particularly became prominent as it is widely believed that stakeholder's views and preferences can help shape decisions and evolve energy system designs that are implementable (i.e. workable), and that will be regarded as sustainable in the long run (i.e. in terms of environmental friendliness, social acceptability and economic competitiveness) [24, 25]. Thus, a sustainable energy system must not only be able to produce energy at or for a particular environment, society or economy in the present, it must also be able to produce enough energy to support continuous socio-economic functions going into the distant future, with minimal conflicts expected to arise across associated impact categories and dimensions as adjudged by the viewpoint of relevant stakeholders.

3 How to Measure the Sustainability of Energy Systems

This section describes how to measure the sustainability of energy systems, bearing mind that energy sufficiency is the principal determinant of the sustainability of energy systems.

Since sustainable energy systems must produce enough energy to support continuous socio-economic functions while also eliciting minimal conflicts across different impact categories and dimensions as adjudged by relevant stakeholders, measuring its sustainability should be done using indicators that (i) measure the sufficiency of energy systems based on agreeable reference systems; (ii) quantifies benefits and impacts across other impact categories and dimensions; (iii) are sensitive to spatial and temporal considerations; (iv) are understandable by relevant stakeholders.

3.1 Measuring Sufficiency of Energy Systems

Before the industrial revolution of the 19th century, energy systems just produced sufficient energy for human survival and ensuring the sustenance of the mostly agrarian global economy [28–32]. Most of energy was used for cultivation and irrigation of land; digging of earth for water, minerals and treasures; harvesting of timber, crops and water; processing and transporting of food, water, other biomass and minerals (metallic and non-metallic); as well as making fire for heating and lighting purposes, as well as protection from predators [16, 29]. Energy use was mostly driven by human and animal labour (i.e. use of human/animal energy slaves), as well as modest windmill and water driven innovations [17, 28]. The discovery of fossil fuel (initially coal, then later petroleum and natural gas) made far much more energy available and led to significant inventions in the textile, food, steel and railway transport industries, first in Europe, then globally [18, 30]. The discovery of fossil fuel led to accelerated growth in the global manufacturing industry [2, 32]. There was growth in inventions from the light and heavy machineries industries as signalled by the making of aircrafts, large shipping vessels, military armoured tanks and weaponries, passenger and freight vehicles, tractors and cranes, as well as other lofty and noteworthy innovations in the global building and construction sectors [18–20]. Then came the emergence of computer innovations and automation which gave a facelift to every sector and sphere of the fossil fuel driven global economy [7, 31]. The computer and automation age improved human life, culture and existence significantly, triggered significant global economic growth, but also led to the redundancy of human and animal labour as sources of energy [33–36].

Increased awareness on the massive and continuous depletion of global fossil fuel resources (made famous by the Hubbert Peak Theory in the 1960s etc.) on the one hand [13, 15], and the widespread education on the adverse environmental impacts of fossil fuel driven energy systems and economy (starting from the 1950s and reaching a fever pitch in the 1990s/2000s) on the other hand led to a gradual and later massive shift of attention to the need for alternative renewable energy systems [20–22]. However, since discussions around replacing fossil fuel driven energy systems with renewable energy systems became mainstream, there has been continuous doubts on the capacity of renewables to produce sufficient energy to sustain the current civilization built almost entirely on fossil fuel driven energy systems (almost 90% of global energy systems still runs on fossil fuel) [37, 38]. Consequently, the capacity of energy systems (either fossil fuel or renewables) to produce sufficient energy to support continuous socio-economic functions or contribute to the sustenance of human civilization have been measured in a variety of ways using net energy indicators [7, 39]. Net energy indicators measure the capacity of energy systems by estimating how much energy is left for societal distribution and/or use after factoring in as many inputs as possible or as can be quantified [24, 40]. Net energy indicators are of utmost importance within sustainability assessment of energy systems because energy sufficiency (i.e. net energy) is a principal or primary determinant of the sustainability of energy systems [40–42]. The existence and continuation of life on earth in itself (either natural or human dominated) is first a function of the net energy derivable or made available to such systems [2, 3]. Lack of sufficient net energy in natural systems lead to species extinction, lack of sufficient net energy for driving human civilization leads to the collapse of human societies [1, 5]. The other benefit or impact categories (other than energy sufficiency) that deserve considerations within the context of sustainability of any energy system can be considered secondary or an appendage to net energy because all natural and human activities depend first on the availability of sufficient energy [5, 42]. Since nature and human systems (i.e. socio-economic systems) mimic each other, the amount of net energy available in nature or to a human society determines the magnitude of growth and development possible either in nature or within human societies [1, 7]. Net energy indicators therefore directly or indirectly account for a large number of auxiliary benefits and impact categories associated with energy systems [41–45].

Even though several net energy indicators have been applied in sustainable energy literatures, most of them were derived from two primary ones. The first one is the net energy gain or the net energy balance, which is estimated by subtracting total energy input considered from total energy output obtainable (i) [46–49].

$$\begin{aligned}&\text{Net Energy Gain (NEG) OR Net Energy Balance (NEB)}\\&=\text{Total Energy Output}-\text{Total Energy Input}\end{aligned}\tag{i}$$

The second one is the energy return on investment (EROI) or the energy return on energy invested (EROEI), which is the fraction or ratio of net energy obtained after consideration of all relevant energy inputs and outputs (ii) [40–44].

$$\begin{aligned}&\text{Energy return on investment (EROI) OR the energy return on energy invested (EROEI)}\\&=\text{Total Energy output}/\text{Total Energy Input}\end{aligned}\tag{ii}$$

NEG or NEB estimates the net energy obtainable by an energy system either on a per unit level or on an economy-wide basis [24, 50]. On a per unit level, the amount of energy added by an energy system on unit basis is estimated [48, 49]. On an economy-wide level, the amount of energy that can be added by an energy system to the economy or society or to the fulfilment of local, regional or national renewable energy targets, as well as other energy objectives can be more accurately measured [46, 47]. Using NEG or NEB is more accurate for assessing progress of energy transition targets/objectives or the capacity of energy systems to meet energy transition systems/objectives than the use of gross energy indicators that measure only the outputs of energy systems [27, 46].

EROI or EROEI is the fraction or ratio of net energy delivered by an energy system to a particular environment, society or economy [51, 52]. It can be measured at different stages of the energy production, distribution and use chains, based on trade pre-conditions or based on usefulness or benefits to the economy or society (Table 1).

$\text{EROI}_{\text{soc or}}$ EROI_{eco} is the ratio/fraction of total net energies available for production of goods and delivery of services from all energy systems within a society or an economy [39, 57]. It is often estimated as the ratio of energy returned to the society from all economic activities within the society to the energy required to perform all economic activities within the same society [40, 45]. It has also been calculated as the ratio of productivity within an economy (in monetary terms or GDP terms) to the energy cost of productivity within the same economy (also in monetary terms) [44, 56]. This is based on the assumption that money/price of goods and services are interrelated and can be denominated in terms of energy [41, 51].

EROI is however more widely used than NEG because it is a direct and proxy indicator of many impact categories across different impact dimensions/spheres (i.e. environmental, social and economic impact dimensions for the sustainability of energy

Table 1 EROI measurements across value chains, based on trade preconditions and usefulness/benefits to the economy/society

EROI measurements	Description
Classification based on value Chain [51–53]	
EROI_{std} or $\text{EROI}_{\text{minemouth}}$ or $\text{EROI}_{\text{farmgate}}$ or $\text{EROI}_{\text{waste source (landfill/dump site/bin)}}$	EROI after resource extraction (minemouth for fossil and mineral based raw materials for energy production; farmgate for cultivation and harvesting of bioenergy feedstock; waste source for waste biomass feedstock from landfill, dump sites and bins)
$\text{EROI}_{\text{ref or}}$ $\text{EROI}_{\text{prod}}$	EROI after refining or production
$\text{EROI}_{\text{distr}}$ or $\text{EROI}_{\text{trans}}$ or EROI_{pou}	EROI after distribution, transportation or transmission i.e. point of use
$\text{EROI}_{\text{use,}}$ EROI_{ext} or NER	EROI of use or extended use or net energy ratio
Classification based on trade preconditions [53, 54]	
EROI_{dm}	EROI of domestic energy supplies
EROI_{im}	EROI of imported energy supplies
Classifications based on usefulness/benefits to the economy/society [55–59]	
EROI_{eco} or EROI_{soc}	EROI of a society or economy

systems) [27, 60]. While NEG has only been used as an indicator for measuring the sufficiency level of energy systems at unit level or with regards to set energy policy targets/objectives, EROI has been applied in many more ways as a sufficiency indicator of the capacity of energy systems to support affluence/long lasting prosperity [40, 41]; capacity of energy systems to eradicate poverty, obtain certain quality of life and social well-being, as well as to attain certain levels of economic development [24, 41]. Previous studies have provided reference systems for comparing the significance of NEG and EROI for different impact categories (Table 2).

EROI is also a proxy indicator of the impact of production costs and environmental remediation/protection costs etc. [24, 58]. Since price and energy are deeply interrelated, rise or drop in EROI can be an important predictor of future price levels within an economy, as well as an indicator of long lasting profitability of energy ventures, as well as prosperity of other businesses and services within an economy (since they all depend on energy) [56, 63]. The 2008 global economic meltdown was triggered by an initial drop in EROI of global fossil fuels (the primary energy supporting the world's economy) [7, 64]. EROI has also been used as an indicator for socio-economic metabolism and global energy systems transition [31, 65]. Pre-industrial revolution (agrarian economies based mostly on renewables) had an EROI of about 2–3:1 [29, 32]. Empires/civilizations (e.g. Roman empire) fell when there was drastic decline in EROI as a result of low crop yields occasioned by soil degradation [30, 66]. Fossil fuel powered industrial revolution had an EROI of greater than 20:1 at the beginning of the 20th century (up to 80:1 around 1950s for US coal, up

Table 2 Net energy systems, impact categories and reference systems

Net energy indicator	Impact category	Reference system
NEG	Unit-level energy provision	Positive NEG values implies that energy system is net energy positive i.e. energy system has overall potential net energy gain. This means that the usefulness of the energy system to the society is not in doubt [24, 27] Zero or close to zero NEG values implies that energy system is net energy neutral i.e. energy system has neither positive nor negative net energy. This means that even though the energy system produces energy, its usefulness to the society is very limited [46, 47] Negative NEG values implies that energy system is net energy negative i.e. energy system has overall negative net energy. This means that the even though the energy system produces energy, it is of no net use to the society, hence thermodynamically useless [48–50]
	Economy-wide energy provision	% contribution to set renewable or general energy targets/objectives [46, 47]
$\mathrm{EROI}_{\mathrm{soc}}$	Agrarian based economy	$\mathrm{EROI}_{\mathrm{soc}}$ of 3:1 and below but not less than 1:1 [31, 32]
	Industrialized economies (US and other OECD countries)	$\mathrm{EROI}_{\mathrm{soc}}$ of 11.1 and above [57, 59]
	Fall off of human civilization	$\mathrm{EROI}_{\mathrm{soc}}$ of 10.1 and below [40, 61]
	Developing economies	$\mathrm{EROI}_{\mathrm{soc}}$ of 10.1 and below [51, 52]
	Threshold for improvement in wellbeing	$\mathrm{EROI}_{\mathrm{soc}}$ of between 20:1 and 30:1 [41]
	Moderate to poor quality of life	$\mathrm{EROI}_{\mathrm{soc}}$ of below 25:1 [41]
	Levelling of improvements in wellbeing (i.e. no further improvement possible)	$\mathrm{EROI}_{\mathrm{soc}}$ of 30:1 and above [41]

to 65:1 around 1970 for Canadian oil and gas) but has declined continuously over the last century to around 10:1 and below due to increase in fossil fuel extraction and remediation costs, as well as depletion of global fossil fuel reserves [41, 52]. Most renewable energy systems (biomass and solar photovoltaics especially) seen as replacement to declining fossil fuel-based energy systems currently have EROI of less than 10:1 (same as fossil fuels) [40, 61], with a few having EROI values above

the minimum expected from a sustainable primary energy source i.e. 11:1 [57, 59]. Solar photovoltaics is believed to have an EROI of at least 10:1 by Raugei et al. [67], and ≤3:1 by Prieto & Hall [68]. Wind is one of the few renewable energy sources with an EROI above 11:1 (~18:1) [40, 69]. While uncertainties associated with differences in EROI indicator values obtained has been identified as major drawback of using the EROI indicator, the discrepancy in indicator values has been attributed to difference in estimation boundaries and assumptions of study, as well as difference in conversion factors associated with the different energy input and energy output estimations [70, 71].

With regards to the application of EROI as an indicator for tracking energy systems transition, and as a response to a drop in EROI of primary energy systems within particular economies, an EROI derived indicator namely gross energy requirement ratio (GERR) has been devised by Murphy [59] for determining the net energy ratio that a new energy system needs to have to sustain an economy experiencing a fall in EROI of its energy systems. The application of net energy-based NEG and EROI indicators for measuring the energy sufficiency of energy systems (either fossil fuel based or renewables) is an integral part of determining their sustainability and should therefore be regarded as such [46, 47]. Estimating NEG and EROI indicators should be therefore be prioritized within the context of sustainability assessment of all energy systems [48, 49]. Their usefulness as direct and indirect (proxy) indicators of several sustainability impact categories and dimensions further justifies this position [20, 27].

3.2 Quantifying Other Benefits and Impacts Across Impact Categories and Dimensions

Despite the fact that NEG and EROI based indicators can be applied as direct and proxy indicators of several sustainability benefits and impacts as it relates to energy systems, there are still important impact categories and dimension they do not account for either directly or indirectly, hence the need for separate considerations [23, 72]. Even though NEG and EROI may account for some of such impact categories or dimensions indirectly, facilitation of detailed and more accurate decision-making processes requires that some of them be accounted for separately [22, 24]. Within the context of determining and improving the sustainability of energy systems (either fossil fuel driven or renewable), as well as making choices with regards to shift of attention to renewable energy systems, common benefit and impact indicators or metrics that are often required and compared in weighing decisions and making policies are as follows (Table 3).

The relevance of different impact categories to sustainability are often determined contextually by stakeholders. Some impact categories are quantifiable quantitatively [23, 73], while others are hard to quantify and can therefore only be measured qualitatively [24, 74]. Impact categories pertaining to the effects of energy systems on

Table 3 Sustainability impact categories, dimensions and nature

Sustainability impact categories	Sustainability dimensions	Nature of data for impact category
Greenhouse gas balance (for selection of net zero greenhouse emission options or least greenhouse emission options or best carbon emission reduction options) [73–75]	Environmental	Quantitative
Biodiversity impact (e.g. species richness, species rarity etc.) [73, 74]	Environmental	Quantitative
Environmental quality (air, water and soil quality) [74, 75]	Environmental	Quantitative
Job provision (numbers of potentially generated green jobs) [23, 76]	Social	Quantitative
Profitability [24, 77]	Economic	Quantitative
Scalability (i.e. profitability at medium and large scales) [78–80]	Economic	Quantitative
Depreciation potential [74, 76]	Economic	Quantitative
Suitability of enterprise management/control systems (social enterprise, community-based enterprise or corporate driven enterprise etc.) [74, 75]	Economic	Qualitative
Enhancement of social cohesion and harmony [74, 76]	Social	Qualitative
Payback time [in terms of money, energy and carbon [73–75]	Money payback (economic), energy payback (social), carbon payback (environmental)	Quantitative
Social acceptance/citizen's satisfaction [27, 77]	Social	Qualitative
Ecological structures/properties-nitrogen fixation potential etc. [73, 75]	Environmental	Quantitative
Biogeochemical nutrient cycling-carbon cycling, nitrogen cycling, phosphorus cycling, water cycling etc. [75, 78]	Environmental	Quantitative
Human rights/heritage preservation [79–81]	Social	Qualitative
Acculturation/cultural change [51, 80]	Social	Qualitative

(continued)

Table 3 (continued)

Sustainability impact categories	Sustainability dimensions	Nature of data for impact category
Political progress [52, 82]	Social	Either Quantitative or Qualitative
Educational development [41, 83]	Social	Either Quantitative or Qualitative
Job decency-occupational safety and/or security [80–83]	Social	Either Quantitative or Qualitative
Quality of life/social well-being [41, 52]	Social	Either Quantitative or Qualitative
Rural/community development [73, 74]	Social	Either Quantitative or Qualitative
Equal opportunity-Gender/racial equality [51, 76]	Social	Quantitative
Class mobility [79, 80]	Social	Quantitative
Marketability [76, 77]	Economic	Quantitative
Technical/cost efficiency [76–79]	Economic	Quantitative

environmental quality and characteristics are classified as environmental in dimension [27, 75], while others related to the influence of a particular energy system on the costs, prices and accessibility of goods and services (in terms of availability and affordability) can be grouped as having economic dimensions [76–79]. Impact categories that measures the benefits and impacts of an energy system on particular social fabrics, processes and institutions are classified as social in dimension [80–83].

Since several other impact categories and dimensions (other than energy sufficiency) are also key for balanced decision and policy making, a holistic sustainability assessment framework for an energy system must put into consideration other relevant benefit and impact metrics for measuring the different impact categories and dimensions classified as important by concerned stakeholders (i.e. stakeholders concerned with decision and policy making regarding particular energy systems under consideration) [81, 82].

3.3 Sensitivity to Spatial and Temporal Considerations

Indicators used for measuring the energy sufficiency, as well as other impact categories/dimensions relevant for determining the sustainability of energy systems must be dynamic and not static in nature i.e. must be measurable over time and space [59, 81]. This is an essential element of sustainability assessment of energy systems. Future depreciation in net energy values, as well as negative change in the values of other impact category/dimension indicator values due to temporal factors (e.g. energy resource scarcity/exhaustion, increased extraction costs etc.) essentially compromises the future capacity of such energy systems to support continuous socio-economic functions, economic growth/development, as well as sustain or transit from the current fossil fuel powered civilization [24, 61]. Similarly, future phenomenal rise in net energy values (NEG or EROI), positive change in values of other impact category/dimension, possibly occasioned by reduction in difficulty of producing energy i.e. as a result of technological improvements in production and material extraction phases (improvement in energy efficiency of cultivation and harvesting phases for energy biomass extraction) will also improve the future capacity of an energy system to support socio-economic functions, economic growth/development, as well as ensure the sustenance of or transit away from the current fossil fuel driven civilization [27, 62].

The fall of the Roman empire was deeply connected to drop in EROI to below 2:1, occasioned by lower yields and lack of food for feeding the human population (soldiers, labourers and other citizens) and the work animals (horses, cattle, donkey etc.) as a result of soil degradation [30, 32]. The discovery and exploitation of fossil fuel reserves facilitated the transition of humanity from mostly agrarian societies to industrial societies [84–86]. Fossil fuel made significant energy available and culminated in the industrial revolution [31, 57]. The world relied on net energy from fossil fuel until the industry witnessed a drop in EROI due to increase in production costs around 1970s [40, 58]. The drop in EROI was temporarily overcome by technological improvements in extraction and discovery of new reserves between the 1980s and 2000s before witnessing another decline due to increasing production and remediation cost, as well as further depletion of fossil fuel reserves globally [85, 87]. Heightened enlightenment on the negative impacts of exploitation and use of fossil fuel (principally global warming and climate change), realization of gradual extinction of global fossil fuel reserves, and admittance of the limits of technological improvements in extraction of fossil reserves has jointly facilitated a shift of attention to the development of renewable energy systems globally [19, 89]. Most renewable systems however have lower EROI indicator values than fossil energy carriers with most systems having EROI values less than 10:1 net energy ratio (e.g. biomass and solar photovoltaics etc.) and a few having more than 11:1 (e.g. wind etc.) [40, 69].

While it is noteworthy that biomass, solar photovoltaics and wind energy systems has the widest appeal of the known renewable energy systems (others including waves, tides, ocean currents, geothermal etc.), their current EROI values puts a limit on their outlook as virile replacements for fossil energy systems [42, 88]. Biomass, solar photovoltaics and wind like fossil fuel should be expected to peak and plummet going forward due to projected future increase in cost of extracting materials for production of biomass plants, wind turbines, solar panels, photovoltaic batteries, wind energy storage systems and other accessories [86, 89]. Competition for and cost of land for renewable energy system development is also expected to play a future role in the decline of EROI of renewable systems [90, 91]. Aside land use for renewable energy systems development, other competing land use activities expected to culminate in a peak demand for land are increasing food, raw materials, urban development and climate change mitigation demands (e.g. forest and wetland preservation etc.) [40, 42]. Owing to the fact that assessing the impact of these temporal factors are important for determining the sustainability of energy systems, indicators sensitive to assessing their impacts on sustainability ought to be prioritized within sustainability assessment frameworks for energy systems [24, 27].

Renewables (biomass, solar photovoltaics, wind and other climate dependent energy systems) are assumed to be more productive in terms of energy outputs in the tropics and Global South (mostly developing countries) where climate systems are considered relatively more active (due to higher incident sun) than in the temperate and global North regions (mostly developed countries), where climate systems are considered less active [92–94]. Renewables are projected to have higher energy productivity potentials in the Global South not only because of the higher incident sun but also because of the relative availability of land [93–96]. The reliance of renewable energy systems in these regions (i.e. tropics and the Global South) on imports however has some rarely considered impacts on the eventual net energies delivered by such renewable energy systems to the society [53, 95]. Also, the chaotic and uncertain nature of the more active weather systems in the region, as well as variabilities and vulnerabilities associated with climate change makes the projected potential of these mostly climate dependent renewable systems uncertain [97, 98]. Much more than expected from temperate and Global North regions, land competition is expected to become fiercer in the Global South due to high speculations on the potentials of relatively cheaper renewables as the energy system of the future, need for future expansion of croplands, pasturelands and urban spaces (necessitated by food and raw material needs of the growing population), as well as the needs to preserve global carbon sinks, as there are far more expansive forests and wetlands in the Global South than in the Global North e.g. Amazon Forest Basin, Equatorial Congo forest Basins etc. [99–101]. Since assessing the impacts of these spatial factors are important for determining the sustainability of the energy systems under consideration, indicators sensitive to assessing their impacts on sustainability ought to be prioritized in sustainability assessments of energy systems [27, 99]. Other pertinent spatial factors that separate energy systems in the temperate and Global North (mostly developed countries) from those of the tropics and Global South (mostly developing countries) include culture, gender, poor energy and other supporting infrastructure (e.g. bad transportation and distribution channels/networks, weak/obsolete energy grid infrastructure, high transmission losses etc.), weak institutional and policy implementation frameworks etc. [102–105].

3.4 Comprehensibility by Stakeholders

An important feature of indicators suitable for deployment in sustainability assessment of energy systems is comprehensibility by stakeholders [20, 23]. Indicators applied (either net energy based or not) for assessing the sustainability of energy systems, as well as for evaluating the impacts and benefits of energy systems on impact categories/dimensions should be understandable by the stakeholders involved in the decision and/or policy making processes regarding the energy systems [24, 82]. The role of stakeholders within the determination of the sustainability of energy systems include the interrogation and analysis of indicator results (either quantitative or qualitative), establishing a consensus on the most important indicators that describe specific impact categories/dimensions, identifying and weighing the relative importance of impact categories/dimensions considered most relevant for the energy systems under consideration (based on the spatial and temporal characteristics of the energy system), arriving at decisions on the most relevant impact categories/dimensions for each energy systems evaluation, setting the criteria for the most sustainable energy systems options, analysing conflicts and trade-offs associated with choices made, choosing the best options among several energy systems based on information available (e.g. indicator values, projected energy system benefits and impacts across impact categories/dimensions over space and time etc.), validated computer algorithms (e.g. multiple GIS operations in a spatial multi-criteria assessment context-SMCA, Analytic hierarchy process-AHP, Preference ranking organization method for enrichment evaluation-PROMETHEE, MAUT-Multi Attribute Utility Theory, Elimination and Choice expressing Reality-ELECTRE etc.), as well as individual/group perceptions [83, 106].

There are two kinds of stakeholders within every sustainability assessment context namely the decision/policy makers and the decision/policy takers [24, 107]. Decision/policy makers are stakeholders that are directly involved in the making of decisions and/or policies regarding a particular sustainability issue under examination, while decision/policy takers are those principally affected or impacted by decisions and/or policies made regarding a sustainability issue under consideration [27, 108]. The views and perspectives of both kinds of stakeholders are equally important for arriving at strategies for improving energy systems on the one hand, as well as choosing better options among different energy systems on the other hand. There might be an overlap of functions between decision/policy makers and decision/policy takers under certain sustainability assessment context, hence no need for duplication of functions when determining the composition of stakeholders for energy systems evaluation [24, 82]. The composition of stakeholder representation needed for balanced sustainability assessment of different energy systems usually vary by case, but it is most often dependent on the nature of the value chains involved in the production, distribution and use phases of such energy systems [23, 109]. Streamlining the choices of stakeholder to be represented in each sustainability assessment context for different energy systems is often dependent on what is included in or excluded from the boundary of decision/policy making processes under consideration [25, 75].

4 Need for Sustainability Assessments and Elements of Holistic Sustainability Assessment of Energy Systems

This section highlights the need for holistic sustainability assessment of energy systems and discussed the elements and sub-elements of holistic sustainability assessment of energy systems.

From Sect. 3, it is clear that conducting a holistic sustainability assessment for an energy system in order to have a comprehensive grasp of its essence in entirety requires multiple layers of information [24, 81]. Obtaining and synthesizing the diverse information needed for weighing the impact of decisions/policies to be made, and arriving at balanced decisions/policies that can be contextually regarded as bearable, viable and equitable in the long run, especially with respect to relevant impact categories and dimensions will be a daunting task [23, 110]. In undertaking such onerous task i.e. providing the several layers of information needed to ensure a balanced and fair sustainability assessment for energy systems, there is need to put the basic elements of such laborious assessment in retrospect [27, 111]. The basic elements will help determine the data and information requirements of sustainability assessments of energy systems from the onset before embarking on such tedious study [25, 112]. The identified elements of sustainability assessment of energy systems from this study as detailed in Sect. 3 are space, time, impact and stakeholder elements [110–112]. This can be summarized in an acronym called STIS i.e. space, time, impact and stakeholders [24, 27]. The use of these elements of sustainability assessment for energy systems will help answer the where, when, what (comprising of how and why) and who sustainability questions regarding energy systems (Fig. 1) [27, 110]. With regards to space (answering the where sustainability questions), like every other sustainability issue, the boundaries of the sustainability of an energy systems can be regarded as local or regional in extent, and may also be global in dimension if its impact is felt globally (e.g. air pollution contributes to global warming) or if it is impacted by a global phenomenon (e.g. local occurrence precipitated by global climate change or global COVID 19 pandemic) [26, 114]. With regards to

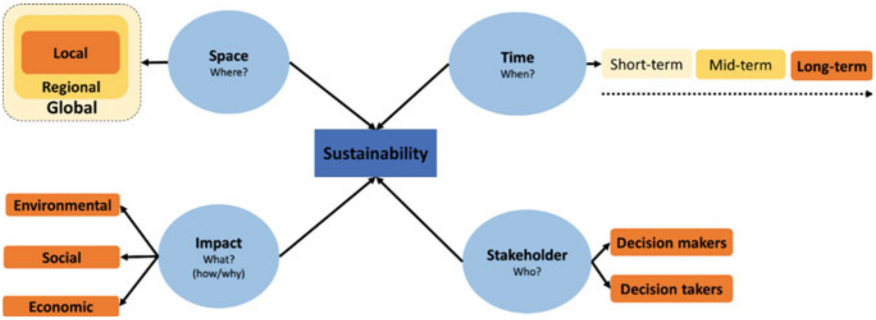

Fig. 1 Pictorial description of the Space, Time, Impact and Stakeholder (STIS) sustainability conceptual structure (elements and sub-elements of a holistic sustainability assessment)

time (answering the when sustainability questions), the sustainability of an energy systems can be affected by one event, a trend of related events, series of independent events or combinations of events, some or all of which may have short-term impacts, short-to mid-term impacts as well as long term impacts [24, 111]. With regards to impact (answering the what sustainability questions, either in form of why or how sustainability questions i.e. cause and effects), the impact categories identified as relevant and examined within the context of sustainability assessment for energy systems may be environmental, social or economic in dimension [21, 110]. They may also be an overlap of any two or three of the impact dimensions [22, 23]. With regards to stakeholder (answering the who questions), the sustainability and design of an energy system can either be viewed from or influenced by the decision/policy maker point of view or the decision/policy taker point of view [27, 113]. A combination of both is also possible especially when there is an overlap of functions between the two stakeholder groups [82, 110].

Visualizing the data needs of sustainability assessment of energy systems at a glance as done via the STIS conceptual structure for description of the elements and sub-elements of sustainability assessments (Fig. 1) helps break the tasks into smaller units (however tedious). It also aids the identification of the elements and sub-elements of sustainability assessment covered by each methodology or a combination of methodologies to be deployed within the framework of the sustainability assessment of the particular energy system under consideration [24, 27].

5 Choices of Methodologies and Methodological Frameworks for Holistic Sustainability Assessment of Energy Systems

After determining the data and information requirements required to answer all sustainability questions, next will be making choices regarding the methodologies or combinations of methodologies to be adopted for providing the data and information requirements, answering the different sustainability questions, as well as addressing the different elements and sub-elements of holistic sustainability assessment as described in Fig. 1. This section discusses the choices of methodology and methodological frameworks available for sustainability assessment of energy systems, and demonstrated the use of the STIS conceptual structure for assessing their adequacy in providing all data and information needed for answering all relevant sustainability questions and covering all sustainability assessment elements and sub-elements in a holistic manner.

While some methodologies answer questions across only one element or sub-element of sustainability assessments, some answer questions across several more elements and sub-elements [27, 110]. Most sustainability assessments rely on combinations of methodologies to answer all questions and cover all elements and sub-elements of sustainability assessments. Previous studies on holistic sustainability

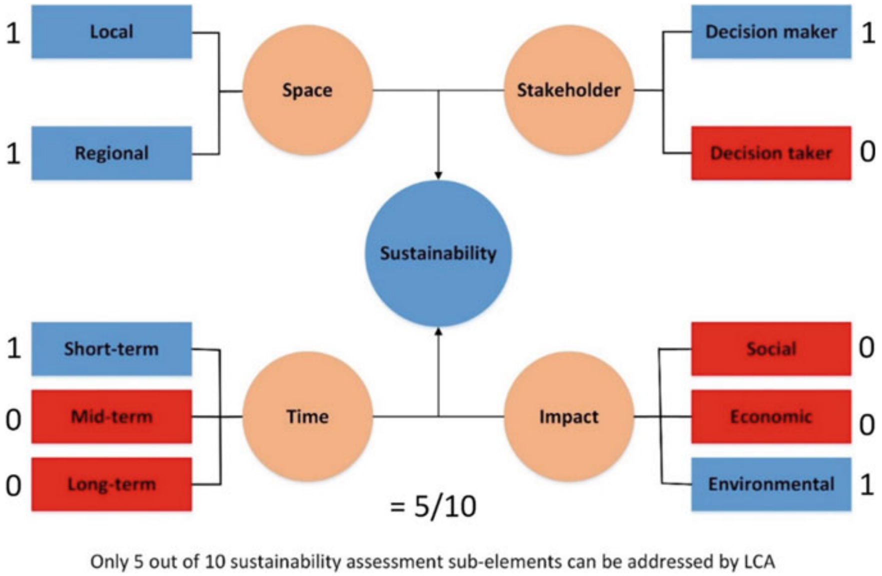

Fig. 2 LCA evaluation as a holistic sustainability assessment methodology for sustainability assessment of energy systems [24, 27]

assessment of energy systems found that the application of life cycle assessment (LCA) for sustainability assessment of an energy system usually cover only five out of ten sub-elements of a holistic sustainability assessment framework (as described by the STIS conceptual structure for description of elements and sub-elements of sustainability assessments) [24, 27]. This imply that LCA needs to be combined with other methodologies to achieve completeness with regards to the data and information needed in order to ensure that the sustainability assessment is comprehensive and holistic (Fig. 2).

Different methodologies for answering different sustainability questions and covering different elements and sub-elements of sustainability assessments, especially as it relates to energy systems can found in Fig. 3. Generally, questions on space can be answered by remote sensing, geographic information systems [4, 47]; questions regarding time can be answered by historical records and prediction/simulation models [27, 31]; questions regarding impact can be retrieved from cause and effect analysis (e.g. statistical tests-regression modelling, correlation analysis etc.) and/or impact assessment studies/tools (e.g. life cycle assessment, life cycle sustainability assessments, environmental impact assessment, policy impact assessment, strategic environmental assessment, gender impact assessment, participatory impact assessment etc.) [20, 115, 116]; while questions regarding stakeholder can be answered by information obtained from interviews, surveys, stakeholder workshops/engagement forum (in form of Likert scale, percentages, fractions, ratios, Bayes probability etc.)

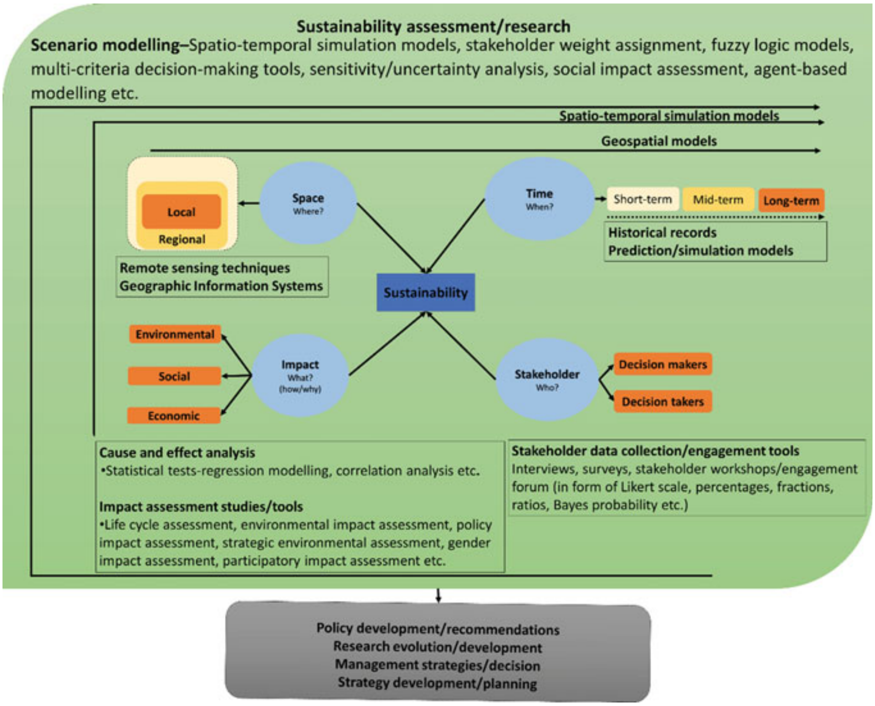

Fig. 3 Methodologies adaptable for provision of information across the different elements of sustainability assessment of energy systems

[82, 108]. Questions on impacts over space and time can be quantified by spatio-temporal simulation models [24, 89]. Stakeholder preference/impact over space and time is often elicited by creating scenarios and simulating their impacts using spatio-temporal simulation models, spatial decision support systems, spatial multi-criteria evaluation, assignment of stakeholder's weight, fuzzy logic models, multi-criteria decision making tools (e.g. AHP, ELECTRE, PROMETHEE, Analytic network process-ANP etc.), sensitivity/uncertainty analysis, social impact assessment, agent based modelling etc. [82, 83].

6 Features of Holistic Sustainability Assessment Frameworks for Evaluating Future Energy Systems: Limitations and Sustainability Pathways for Renewable Energy Systems

Since the dominant energy systems globally (i.e. fossil fuel driven energy systems) are on a decline, and renewable energy systems are already considered as the energy systems of the future, there is an existential need to briefly discuss their limitations and future sustainability pathways, especially because their estimated net energy indicator values (the principal sustainability indicator and determinant) casts shadows of doubts on their future sustainability [40, 51]. Future sustainability assessment framework for energy systems must be holistic and based on prevailing understandings on the nature of energy systems projected to become more dominant (i.e. renewable energy systems) as the fossil fuel era gradually winds down [31, 92]. Consequently, this section discussed the limitations of renewable energy systems already identified and speculated on their future sustainability pathways (i.e. strategies for overcoming their limitations and improving their sustainability). Based on the limitations discussed and the sustainability pathway offered, this section came up with likely features of holistic sustainability assessment frameworks for evaluating future energy systems.

6.1 Limitations of and Sustainability Pathways for Renewable Energy Systems

Already identified limitations to the capacity of renewable energy systems to support continuous socio-economic functions and sustain the current fossil fuel driven global civilization include expected future depreciations in net energy deliverable to the society as result of (1) projected scarcity of/increase in production costs of materials used for energy production (i.e. biomass plants, wind turbines, solar panels, photovoltaic batteries, wind energy storage systems and other accessories) [68, 86]; (2) environmental and economic cost of importation of infrastructures for renewable energy production (especially for Global South); [92, 93] (3) projected increase in land use footprint of renewable energy development projects [90, 91]; (4) susceptibility of renewable energy systems to climate change variabilities (as a result of their dependency on climate systems) [98, 99]; (5) disproportionate energy costs and longer payback time of scaling up [95, 96] and (6) the reliance and path dependency of renewable energy production systems on fossil fuel energy carriers, as well as the associated lock-in-effects [40, 97].

In order to overcome the limitations and improve the sustainability of renewable energy systems going forward, the following measures need to be taken:

- Materials for production of the needed renewable energy infrastructure should be sourced locally and regionally to improve and/or maintain the net energy delivered to the society [117, 118]. This can be done via launching new prospecting activities for minerals used for production of materials needed for renewable energy development [40, 69]. The prospecting can be done both on old mining sites, as well as on undisturbed rock outcrops using appropriate geophysical methods [41, 88]. Domestic (local and/or regional) production of materials for renewable energy generation will reduce and/or check future costs of production [67, 119]. Local renewable energy development capacity can be further enhanced by reliance on reuse and recycling of material wastes [68, 120]. While this may lead to the production of less durable infrastructures with less tensile strength (i.e. entropy effects), the manufacture of composite materials from material wastes can play a role in this regard [68, 121]. The implementation of reuse and recycling of material wastes as a strategy in the development of local capacity will also reduce the pressure on global mineral resources, hence slowing down their depletion rates [122, 123]. Reuse and recycling can be deepened within production and business models for manufacturing of renewable energy infrastructures via adoption of innovative circular economy strategies [19, 72]. Examples of such strategies include the cascading use of material resources [124–127]. This involve repetitive use of materials (via re-use and recycling) before disposal, OR in order to avoid disposal [119, 125, 128, 129]. This is against the norm (i.e. conventional linear economy) where the next destination for materials after an initial use phase is disposal in landfills or compositing (for organic wastes) [121, 126]. This will reduce the energy cost of material extraction (for wind and solar photovoltaic energy systems), as well as the energy cost for cultivation, harvesting and waste collection (for biomass), thereby avoiding future crash in net energy obtainable from renewable energy systems (as the case was for fossil energy driven systems) [125–127]. Cascading use of material resources will also lengthen the value chains of renewable energy systems thereby increasing associated commercial production activities and providing more green jobs [119–123]. However, a major drawback of cascading use of materials (same as individual reuse/recycling activities) is the entropy effect i.e. materials used for energy production in one form tend to get successively weaker in strength after each use (via re-use or recycling) [72, 130]. The manufacture and use of composite materials can however help overcome the entropy effects of cascading use of materials [19, 131].

- Enhancing the productivity, net energy and sustainability of renewable energy systems in the tropics and Global South can only be achieved if the energy systems are weaned off the influence of imports via domestic (local and/or regional) production of renewable energy infrastructures and adoption of innovative circular economy strategies as mentioned above [117–119].
- The land use footprint of renewable energy systems can be reduced by co-production of biomass (either for food, energy or raw materials) with wind and solar photovoltaics. This can be done on any form of land available i.e. forest, cropland, pasturelands, deserts and even urban lands [72, 132]. In urban areas or on urban features in rural areas, food, energy or raw material biomass can be produced in human living spaces such as home gardens, flat and gently sloping roofs, window slabs, pots, old plastic containers, walls, balcony spaces, frontage and backyard spaces and passages [47, 133]. Solar photovoltaic panels and mini-wind turbines can also be accommodated on flat and gently sloping roofs for production of energy [67, 117]. Rather than losing productive lands to wind and solar photovoltaics, co-production of biomass with solar and wind energy can be mutually beneficial [47, 68]. Wind turbines has been observed to mix the air and regulate local day and night temperatures for crops (thereby avoiding day heat stress and night frost) [134, 135]. Wind turbine act as windbreaks, reduces the

amount of dew on leaves thereby lowering incidences of fungal crop diseases [136, 137]. Wind turbines also make more carbon dioxide available to crops thereby aiding photosynthesis [138, 139]. Solar photovoltaic panels have been observed to increase moisture absorption and protect crops from heat stress hereby aiding photosynthesis [140, 141]. Specifically, the land use footprint of bioenergy can be reduced by agricultural intensification upstream and sharing of the same space and resources by different conversion technologies downstream [72, 142].

- Climate change variabilities can be managed via adaptation and mitigation strategies [94, 95]. The impact of climate change on solar and wind can be minimized via the use of more efficient solar battery storage systems, as well as wind energy storage systems [143, 144]. Maximizing the net energy returns from biomass energy systems in the climate change era require careful choice of biomass types, cultivation systems, conversion technologies, scale of production and implementation structure [24, 27]. Biomass energy systems are particularly important because while they provide feedstock for production of renewable heat and electricity, they are also capable of direct replacement of the use of fossil fuel resources for transport fuel, and as raw materials for chemical production [145, 146]. Wind and solar photovoltaics can generate energy to meet electricity and heat demands but not transport fuel and chemical raw material demands [72, 92]. Waste biomass (from forest residues, crop residues, animal manure, homes/offices/industries etc.) deliver much more net energy to the society than cultivated biomass [46, 47]. Cascading use of waste biomass further lengthens its value chain while providing more net energy to the society [147, 148]. Cascading use of waste biomass is however subject to entropy effects which can be reduced via densification and transformation to composite energy fuels (e.g. refuse derived fuel-RDF, solid recovered fuel-SRF, process engineered fuel-PEF etc.) [149, 150]. Energy biomass cultivated on unconventional spaces such as wastelands (sand dunes, old mining/drilling sites, erosion sites etc.), vacant spaces (construction sites, recreational parks etc.), and marginal lands (riverbanks, roadside spaces etc.) provides additional carbon sinks and delivers higher net energy to the society than those competing with other cropland and forest functions [46, 47]. The adoption of short rotation coppice systems and low energy intensity conditions improves the net energy obtainable from biomass-based energy systems e.g. choice of human/animal labour rather than fossil fuel powered machines/vehicles; waste manure/process residues rather than synthetic fertilizers; reduced/no tillage rather than conventional tillage, rainfed or basin irrigation rather than sprinkler or drip irrigation, sowing post-harvest seeds rather than hybrid or GMO seedlings etc. [49, 146]. Adoption of agronomic strategies (e.g. choice of planting/fertilizer application dates and amounts etc.) for improving energy biomass yields without significant energy investments will also help improve the net energy delivered to the society by different biomass feedstock types [24, 27]. Anaerobic co-digestion technology converts several wet waste streams (forest residues, crop residues, animal manure, food waste, sewage etc.) as well as cultivated biomass, and delivers higher net energy to the society than most of other bioenergy conversion technologies [48, 149]. Anaerobic co-digestion technology does not constitute significant environmental burden with respect to water use as it makes use of the moisture content of wet waste. It also does not require significant energy for running the process and drying like other energy conversion technologies e.g. gasification, torrefaction, combustion, pyrolysis, etc. [46, 72]. Digestate from anaerobic digestion can be returned back to the soil as organic fertilizer or soil conditioner or further processed for phosphate recovery (via thermal leaching, struvite crystallization, precipitation of P salts etc.) or converted into other forms of fuel via pelletization (into refuse derived fuel, solid recovered fuel, process engineered fuel etc.), or hydrothermal conversions (carbonization, liquefaction or gasification etc.) [150, 151]. Since biomass can maximize its net energy more at small and medium scales, farms and food processing plants, waste and recycling plants and entire communities can create suitable business models to utilize their own generated wastes (both from fossil and non-fossil sources) thereby reducing energy expended and carbon emissions associated with collection and transport to plants [153, 154]. Implementation of mobile energy production using mobile energy converters (mobile gasifiers, mobile digesters etc.) and generators (mobile combined heat and power systems etc.), rather than situating plants and transporting biomass to them will save energy and money costs on the one hand, and make more net energy available to the society immediately at the end of every biomass transport operation [154–156].

- Since most renewables have net energy less than 10:1 (with the exception of wind with EROI of ~18:1), the net energy delivered cannot support the highest quality of life (affluence) and improvements in well-being [41, 69]. Consequently, there is likely not going to be significant net energy benefits (only a plummet) for scaling up renewable energy systems going forward [86, 157]. Carbon and money payback time for scaling up renewable energy installation will most likely be longer [157, 158]. Biomass, solar photovoltaic and wind energy systems will therefore be more sustainably ran as community based small scale, and at the most medium scale energy projects rather than large scale to maximize their net energy [48, 158]. This will reduce significant energy costs associated with value chain expansions (e.g. transport and distribution) [49, 72]. For instance, fossil energy-intensive biomass cultivation and harvesting procedures, as well as energy-demanding waste biomass collection and haulage operations may become more energy efficient and less polluting if done at small and/or medium scale [24, 46]. It becomes particularly more energy efficient and provides more green jobs and income (however little) if treated as communal good with fossil powered machines and vehicles replaced by human and/or animal labour [27, 48].
- Currently, a significant proportion of renewable energy systems globally cannot survive without fossil energy systems as base energy sources for extraction, production and distribution [40, 68]. In other words, their relatively beneficial net energy supplies are actually subsidized by fossil energy carriers [41, 67]. This creates a path dependency and lock-in effect, as the future net energy of renewable energy systems are dependent on the net energy sufficiency of fossil fuel

[51, 69]. The energy payback time is expected to be longer because a significant proportion of energy invested into the production cycle is fossil fuel based [157, 158]. The dependency of renewable energy systems on fossil fuel energy carriers can be significantly reduced by the diversification of energy portfolios and adoption of new energy mixes globally [52, 92]. While developed countries (mostly in the Global North) might want to favour nuclear as a base energy system, with an EROI of up to 75:1 [158], as well as relative capacity to develop its potential, the choice for primary energy for most developed countries (mostly in the Global South) might be hydropower. Aside EROI estimates of up to 110:1 [159] , up to 267:1 [160], and up to 84:1 [40] for large hydropower installations, as well as EROI of between 41 and 78:1 for mini-hydropower installations [161], hydropower is one of the surviving colonial legacies of most developed countries (especially in the Global South) [92–97]. Most developed countries also do not have nuclear development ambitions due to the constraints and scrutiny associated with doing so [37, 38]. While hydropower is designated as renewable and having it as base energy is in line with global transition towards the dominance of renewable energy systems [160, 161], nuclear energy on the other hand is not yet widely accepted as a renewable energy system due to safety concerns associated with its disposal (especially after Chernobyl and Fukushima nuclear melt down disasters) [162, 163]. The re-designation of nuclear energy as renewables might be considered by many developed countries going forward based on these realities and in anticipation of a future when implementation of nuclear energy generation and decommissioning will be far safer than it is now [158, 163]. The consideration of nuclear energy systems as renewable may be premised on the underlying assumption of reusability/recyclability of nuclear feedstock for further generation of energy after initial use (especially if based on nuclear fission processes) [119, 121]. While research into cheaper nuclear raw materials will enhance the net energy that nuclear energy systems deliver to human societies, adoption of mini-hydro dam models, as well as enhanced flood control and water impoundment strategies will help minimize the likelihood of future decline in the net energy hydropower adds to their catchment communities [159, 161]. Also noteworthy is the fact that both developed and developing countries can tap into the potentials of upgraded biogas as vehicle fuels, as well as for production of heat and electricity (i.e. as natural gas replacement). Biogas has comparatively high EROI values (up to 17:1 for biogas from crop residues [46], up to 33.9:1 for biogas from maize crop [49], and up to 33:1 for biogas from road verge grass [146]). It should be capable of sustaining itself without being subsidized by fossil fuel energy carriers if the possibility is explored [46, 164—166]. It can also be blended with fossil fuel [24, 27]. It can replace fossil fuel as base energy if produced at small-to-medium-scale (especially with maximum transport distance less than 20 km) [49, 167–169].

Going by the continuous and projected future decline in net energies of fossil fuel energy systems, there might be no looking back with regards global transition towards renewable energy systems (their reliance on fossil energy carriers notwithstanding) [37, 51]. This scenario necessitates the need for improving the sustainability of renewable energy systems going into the future [123, 170]. The best time to exploit renewable energy systems after yesterday is today [171, 172]. This is because of projected future decline in societal net energy as a result of expected increase in the cost of production to be occasioned by difficulty in extraction of raw materials for production of biomass plants, wind turbines, solar panels, photovoltaic batteries and other renewable energy accessories [68, 86].

6.2 Features of Holistic Sustainability Assessment Frameworks for Evaluating Emerging Energy Systems

Based on identified limitations of renewable energy systems, as well as strategies suggested for overcoming such limitations and improving the sustainability of renewable energy systems as the energy system of the future (Sect. 6.1), we came up with the likely characteristics of future holistic sustainability assessment frameworks for evaluating energy systems.

Future sustainability assessments of energy systems will focus on evaluation of the short-to-long term environmental, social and economic benefits and impacts of solutions offered to the limitations of renewable energy systems namely enhancement of local production capacity within the context of renewable energy infrastructure development (via material extraction from old and newly discovered mines OR via use of recycled/reused materials), circular strategies and associated entropy effects (facilitated by repetitive reuse and recycling), hybrid heat and electricity mix (from nuclear-renewable energy mix, fossil-renewable energy mix, renewable-renewable energy mix, fossil-nuclear-renewable energy mix etc.), blended transport fuel mix (i.e. fossil fuel + biofuels), co-production (biomass + solar/wind etc.), co-sharing of space and resources for energy conversion and generation activities (e.g. use of same feedstock by anaerobic digester and hydrothermal conversion plant or anaerobic digester and pellet maker etc.) climate change adaptation and mitigation strategies (e.g. better energy storages, choice of feedstock, conversion technology, cultivation systems etc.), community small and medium scale production, mobile energy generation etc.

Expected to be indispensable in future holistic sustainability assessments of energy systems is the role of stakeholder engagement. As new energy systems emerge, some a mix of the old and new energy systems (i.e. fossil and renewable), some applying a mix of circular economy strategies, some a mix of co-producing renewables, some co-sharing space and other resources, there is expected to be conflicts between energy systems and management structures, hence the need to engage the parties involved in order to ensure harmony at different stages of energy project implementation. Within the context of renewable energy transitions, implementation of community-based energy production, mobile energy production, increasing local material/energy content, reducing importation and other strategies for increasing the profitability and net energy of energy systems all require holistic sustainability assessment processes, which stakeholder engagement is an essential part of. In certain cases, new working framework and relationships, as well as attitudinal and behavioural change of energy producers, distributors and users are required to achieve set future energy systems objectives. This cannot be successfully done without getting stakeholders or stakeholder groups to commit to such changes, hence the need to have their input in policy, strategy and decision-making processes regarding energy systems. Incorporation of stakeholders' inputs can be done via stakeholder qualitative assessment, weighing the importance of sustainability criteria, using validated computer algorithms for comparison and narrowing down on options and uncertainty/sensitivity analysis (e.g. spatial multi-criteria assessment (SMCA), AHP, PROMETHEE, MAUT, ELECTRE etc.).

Life cycle perspective is needed within the context of future sustainability assessment of energy systems because entire energy systems are composed of several value chains. Life cycle sustainability assessment of energy systems (a variate of sustainability assessment) is expected to become more prominent going forward as sustainability researchers and practitioners are expected to adopt it as a framework for assessing the benefits and impacts of energy systems. This is because it will bring a life cycle perspective into the assessment of the benefits and impacts of energy systems while retaining the other features of holistic sustainability assessment frameworks i.e. spatio-temporal (short-to-long term) assessment of environmental, social and economic benefits/impacts of future energy systems, as well as stakeholder inputs. Within life cycle sustainability assessments of future energy systems, there will most likely be frequent debates on methods of allocation of benefits and impacts, as well as occurrence and/or avoidance of double counting among different energy carriers in the different energy mixes, in between different co-producing renewables, among different production/conversion technologies sharing same space and resources, along separate value chains associated with conventional and/or mobile energy conversion and generation, as well as in between different circular economy strategies e.g. reuse activities such as maintenance, repairs, refurbishment, retrofitting and repurposing; and recycling activities such as remodelling, remanufacturing and composite manufacturing.

7 Conclusion

In this study, relevance of energy to nature and the society was discussed. The need for sustainability of energy systems was emphasized, while the relevant parameters for measuring energy system's sustainability were enumerated. This study touched on all the important elements and sub-elements of a holistic sustainability assessment framework for evaluation of energy systems. The space, time, impact and stakeholders (STIS) conceptual structure for describing the elements and sub-elements of a holistic sustainability assessment framework for energy systems was presented at a glance. Its adoption as a mind frame for laying out the data and information requirements for holistic sustainability assessment of energy systems was suggested.

Additionally, the STIS systems-thinking frame was recommended for evaluating the deficiencies of information provided by individual methodologies, as well as combinations of methodologies applied for assessing the sustainability of energy systems. The STIS conceptual structure was also proposed as a checklist for determining the combinations of methodologies to be applied for meeting data and information inadequacies, as well as providing the complete information needed from holistic sustainability assessment of energy systems i.e. ensuring that all important elements and sub-elements of the sustainability assessments of the particular energy system under consideration has been duly covered by the combined methodological framework suggested in accordance with the STIS conceptual structure. Finally, we discussed the limitations and future sustainability pathways for the energy systems of the future (mostly renewable energy systems). From the limitations and sustainability pathways discussed, we arrived at the likely features of future holistic sustainability assessment frameworks for evaluating future energy systems namely spatio-temporal (short-to-long term) environmental, social and economic impact assessment of solutions offered, centrality of stakeholder participation and the more frequent adoption of life cycle sustainability assessment methodologies.

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Life Cycle Thinking and Environmental Assessment of Energy Systems from Supply and Demand Perspectives

Mehzabeen Mannan and Sami G. Al-Ghamdi

Abstract This book chapter deals with the application of life cycle assessment (LCA) to sustainable energy systems and technologies around the world. It reviews the practical experiences of LCA application to energy systems and their outcomes in the energy sector. However, as the environmental impact of energy systems can be seen in multiple lenses, the focus of this book chapter has been limited to a critical review of LCA application in electricity generation as a central example of energy supply system along with LCA of energy use in built environment from demand perspective. Critical reviews and related case studies have been presented in this book chapter which will be beneficial for researchers and practitioners in the LCA field to advance their expertise in applying LCA methodology in energy-related technologies. This chapter will also catch the interest of learners/students, as it enables them to have a deep understanding of the diverse environmental impacts from the energy sector, as well as they will get a clear conception of sustainable energy technologies through the comprehensive life cycle analysis.

Keywords Life-cycle assessment (LCA) · Supply and demand management · Sustainable energy systems

1 Introduction

Between the year 1990 and 2018, the global energy consumption has raised by nearly 64% [1]. Fossil fuels (such as coal, oil, gas) continued to play a dominant role in global energy systems, as fossil fuels account for 80% of the global energy production. Starting from the industrial revolution to today's modern technological, social and economic progress, fossil fuels acted as the fundamental driver for the entire global change. However, negative impacts of fossil fuels and overall energy systems on the environment along with the adverse impact of the rapid rate of energy consumption on energy security have amplified the necessity of sustainability assessment of energy

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M. Mannan · S. G. Al-Ghamdi (✉)
Division of Sustainable Development, College of Science and Engineering, Hamad Bin Khalifa University Qatar Foundation, Doha, Qatar
e-mail: salghamdi@hbku.edu.qa

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systems. While taking any decisions about public infrastructure, in this case, the energy systems, the impacts related to the environment need to be assessed [2]. Generally, life cycle assessment (LCA), based on the principle of life cycle thinking (LCT), goes beyond the traditional methods to observe the environmental impact of any product or process. It thereby includes the comprehensive environmental impacts of any product or process over its entire life cycle starting from the raw material extraction to the final disposal phase. LCA of energy systems thus aims reduction in environmental emissions throughout the entire value chain and a major key to observe system sustainability. Currently, LCA is a well-established methodology and have already been deployed widely in the energy sector. The present chapter is an effort to highlight the importance of LCA methodology in various energy systems through critical reviews and case study analysis.

2 Life Cycle Assessment: Definition and Importance

LCA is a powerful analytical tool that comprehensively quantifies the environmental burdens associated with product systems or processes at all stages of their life cycles. According to International Organization for Standardization (ISO): "LCA addresses the environmental aspects and potential environmental impacts (e.g. use of resources and the environmental consequences of releases) throughout a product's life cycle from raw material acquisition through production, use, end-of-life treatment, recycling and final disposal (effectively, from cradle-to-grave)" [3].

Thus, LCA deals with only the environmental impacts of product or process system, excluding economic, social and other factors. It aims to compile and assess the environmental consequences of several available options to fulfil a certain function [4]. For example, imagine a company "A" wants to manufacture a car and thereby trying to finalize whether to use aluminum or steel in terms of reducing environmental impacts. Use of aluminum has the potential to reduce the gasoline consumption compared to steel while aluminum production consumes more energy than steel. Hence, all these factors need to be analyzed to find out the environment friendly option. LCA is a holistic approach that takes into account all the environmental impacts into a single framework, which plays a major role in environmental management in relation to products, which enables LCA to make holistic comparisons among competing product systems [5]. The key direct product applications of LCA include: indication of origins of environmental impacts for a specific product and improvement options, new product design and development, compare between products [6]. LCA is also applicable in a wider area rather than direct product or process, such as in government policies and complex business strategies. According to ISO, the methodological framework of any LCA study includes four distinguished phases:

Goal and Scope Definition: The goal of any LCA study is to explicitly state the reason to carry out the study, intended application and the audience, where the scope of the LCA study includes the functional unit, product system description, system boundary, allocation procedure, assumptions and limitations, impact assessment methods, requirement in data quality [7]. Being an iterative technique, the scope of any LCA study can be modified while conducting the study.

Life Cycle Inventory Analysis (LCI): Life cycle inventory analysis includes collection and quantification of all the relevant environmental input and output data for the entire life cycle of the product system which commonly are the resources used and emissions to water, air and land linked with the product system [8]. The operational steps for the LCI phase include preparation for data collection, data collection, data validation, relating data with each unit processes as well as to functional unit, allocation, aggregation of data, system boundary refixation [3].

Generally, the LCI phase is considered as a straightforward procedure among all the four phases of LCA. Data collection for LCI is a resource intensive process as all the quantitative and qualitative data connected with each unit process within the selected system boundary need to be collected. Based on the goal and scope of any LCA study, interpretation can be drawn from LCI data. However, in most cases, LCI data are used as the input for the life cycle impact assessment phase.

Life Cycle Impact Assessment (LCIA): As explained above, LCI of any product system can include a huge number of resource input data as well as substance emission. Life cycle impact assessment phase aims to translate all the LCI data into meaningful and precise environmental impact scores. Thus, LCIA establishes a linkage between the elementary flows compiled in the LCI phase and their potential environmental impacts [9]. The operational steps in any LCIA according to ISO are impact category, indicators, and characterization model selection; classification; characterization; normalization; grouping; and weighting. At present, several LCIA methodologies are available to conduct the LCA studies, such as CML 2001, Eco-Indicator 99, EDIP'97, EPS 2000, IMPACT 2002+ , IPCC 2001, ReCiPe, TRACI, ILCD [10].

Interpretation: Interpretation is the fourth phase of LCA which combines both the inventory and impact assessment results in order to evaluate and draw conclusions and suitable recommendation for decision and policy- makers. This phase aims to identify the life cycle stages responsible for higher environmental impacts; thus, intervention may significantly reduce the overall impacts of the product system. This systematic technique of interpretation helps to verify the level of confidence in final findings and deliver the results in a complete and accurate way. To achieve these goals, interpretation involves a series of analyses such as sensitivity analysis, uncertainty analysis, contribution analysis, consistency check and completeness check.

3 Sustainability of Energy Systems and Environmental LCA

Although energy sector is a major contributor to global development, however, the production and consumption of energy is often accompanied by environmental burdens and anthropogenic climate change. Production of different kinds of energies (e.g. electricity, biofuels, nuclear, etc.) and their associated environmental impacts are diverse. Similarly, impacts generating from the utilization of energy in different sectors, such as transportation, built environment, vary significantly based on the specification of the end-use. In 2018, 26.9% GHG emission was associated with electricity production (nearly 63% from fossil fuels), recorded as the second highest share of GHG emission in USA after transportation sector (28.2% of the total GHG emission) [11]. The other sectors responsible for high GHG emission in USA were indicated as industry, commercial and residential building, and agriculture.

Impacts resulting from the production and utilization of different forms of energy raised public awareness in both developed and developing countries. Analysis of all upstream and downstream unit processes associated with the entire energy systems is crucial to report a comprehensive climate account of the energy systems. The scope of LCA provides a holistic approach to quantify the impacts of energy systems from cradle to grave. However, as the environmental impact of energy systems can be seen from multiple lenses, the focus of this book chapter has been limited to a critical review of LCA application in electricity generation as a central example of energy supply along with LCA of energy use in built environment from demand perspective.

3.1 LCA for Electricity Generation: Energy Supply Perspective

Today, electricity is considered as the center of modern economics and demand for electricity is predicted to increase by 2.1% every year till 2040 [12]. Although being a clean and relatively safe form of energy during the use phase, the production and distribution of electricity have significant impacts on the environment. Growing electricity demand is one of the key reasons for higher amount of greenhouse gas (GHG) emission from the energy sector. The emissions associated with electricity production and the impacts vary significantly across the country/region due to several factors, such as feature of electricity grid mix, technology used, etc. This section describes the LCA application in electricity generation based on the characteristics of production system. Hence, the first case study reviewed the impacts of electricity generation mostly depended on fossil fuels (Mexico case), while the second case study reviewed the impact of shifting from fossil fuel towards renewable energy for electricity production (Portugal case). Finally, a critical review of clean energy-based electricity production has been covered in this section.

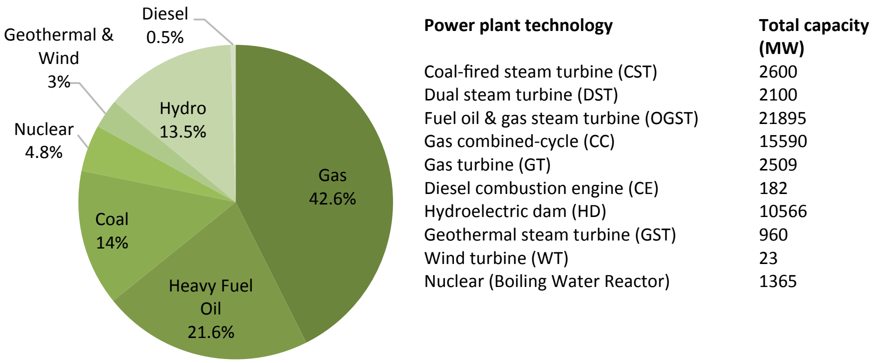
3.2 Fossil Fuel Dominant Electricity Generation: LCA in Mexico

In Mexico, the ever increasing demand for electricity has raised the concern for the environment as the production of electricity has found one of the most polluting sources there. According to 2006 data, fossil fuels account for a major portion for electricity generation, 79% of entire electricity production, while other sources include hydro (13.5%), nuclear (4.8%), geothermal (3%) and wind power (0.02%). At present, fossil fuel is still dominating in the Mexican electricity sector (Fig. 1).

Santoyo-Castelazo et al. performed LCA study based on the public sector electricity generation of Mexico where the functional unit was selected 225 TWh electricity generation in 2006 [13]. For the comparison purpose, this "cradle to grave" LCA study also calculated the environmental impacts of 1KWH of electricity production. Life cycle stages included in system boundaries for this study: fuel and raw material extraction, fuel processing and transportation, power plants construction and decommission, power plants operation and waste disposal (Fig. 2). Background data collection was based on the Ecoinvent database, reflecting the accurate electricity mix data for Mexico. LCA tool GaBi and CML 2001 impact assessment method was employed to assess the environmental burdens in this case. The impact categories included in this study are: GWP (Global Warming Potential); ADP (Abiotic Depletion Potential); AP (Acidification Potential); EP (Eutrophication Potential); FAETP (Fresh water Aquatic Ecotoxicity Potential); HTP (Human Toxicity Potential); MAETP (Marine Aquatic Ecotoxicity Potential); ODP (Ozone Depletion Potential); POCP (Photochemical Ozone Creation Potential); TETP (Terrestrial Ecotoxicity Potential).

Fossil fuel combustion was found to have a major environmental impact in terms of emission to air. Highest CO_2 emission per kWh electricity production was recorded for coal-based power plants, followed by heavy fuel oil, diesel, and gas where heavy fuel oil based plant was responsible for highest SO_2, NMVOC and PM emissions (Fig. 3). Total life cycle CO_2 emission for public sector electricity generation in Mexico was 121.3 Mt while, renewable energy sources were found responsible for less than 1% of the total emission.

Validation of the results has been performed by comparing the global warming potential (GWP100) for the Mexican electricity mix with three other electricity mix (having similar features) findings. The estimated GWP value for Mexico was 571 gCO_2 eq./kWh where the GWP values for UK, Portugal and Italy from Ecoinvent database were 597, 611 and 634 gCO_2 eq./kWh, respectively. Given the similar electricity mix, the difference in GWP values was mainly due to the technology used and efficiency of power generation. Based on the interpretation, this detailed LCA study highlighted that the reduction in heavy fuel oil in the Mexican electricity mix can result in less environmental impact. Moreover, suggestions have made to introduce low carbon-based technologies for future power generation through nuclear power and renewable energy sources.



Power plant technology	Total capacity (MW)
Coal-fired steam turbine (CST)	2600
Dual steam turbine (DST)	2100
Fuel oil & gas steam turbine (OGST)	21895
Gas combined-cycle (CC)	15590
Gas turbine (GT)	2509
Diesel combustion engine (CE)	182
Hydroelectric dam (HD)	10566
Geothermal steam turbine (GST)	960
Wind turbine (WT)	23
Nuclear (Boiling Water Reactor)	1365

Fig. 1 Scenario of power production in Mexico. These data are based on electricity generation in public sector only for the year 2006 [13]

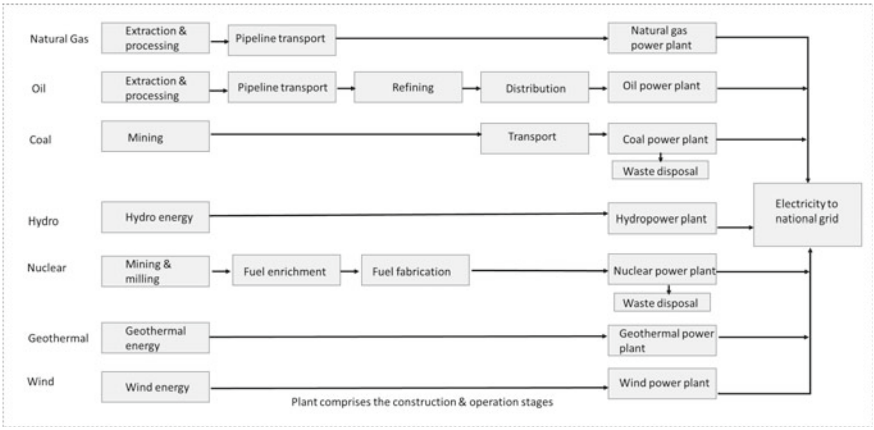


Fig. 2 The life cycle of Mexican Electricity Mix [figure adapted from Santoyo-Castelazo et al. 13]

3.3 *Shifting from Fossil Fuel to Renewable Energy: LCA in Portugal*

In line with the European Union policies, Portugal is experiencing a significant shift in electricity grid mix as the installed capacity of renewable energy has set more than double, especially wind power. The Portuguese electricity mix has aimed to achieve 60% electricity production from renewable sources by 2020. Based on the data of the year 2012, the electricity grid mix includes mainly coal, natural gas, hydropower and wind, covering 92% of the electricity production, where more than 50% of generation is renewable source based. To understand the influence of this significant change in energy sector, process based LCA has been performed covering both electricity

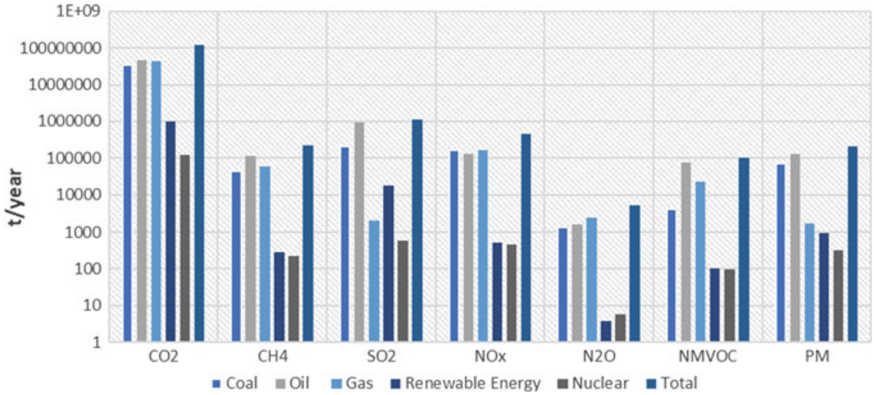


Fig. 3 Selective life cycle environmental burdens from electricity generation in Mexico, in 2006 [Oil comprises heavy fuel oil and diesel]. Figure adapted from Santoyo-Castelazo et al. [13]

production and supply chain (declared as cradle to the plug) for Portugal mainland for the period 2003–2012 [14] (Fig. 4, Table 1).

1kWh of electricity serves as the functional unit for this LCA study. The system boundary includes fuel extraction, processing and transportation; power plant operations; power plant construction and decommission; electricity transmission and distribution grid infrastructure; loses in grid; electricity import and management of waste. The selected impact assessment categories and methods are as follows:

Cumulative non-renewable fossil fuel demand (nREn)	Cumulative energy demand (CED) method
Global warming	IPCC 2007 method
Abiotic depletion, Acidification, Eutrophication, Photochemical oxidation, Ozone layer depletion	CML 2 v2.05 method

Ecoinvent v.2.2 database and technical reports acted as the primary database for LCI. Among all the electricity generation options, the least impacts in all categories came from hydropower option for producing per kWh electricity, however, the impacts in ecosystems due to hydropower were not included in the scope of this LCA study. For impact categories such as acidification (AC), photochemical oxidation (PO), ozone layer depletion and non-renewable fossil fuel demand, the highest impacts were due to the fuel oil-based power plants, whereas coal-based power plants were found responsible for highest impacts in global warming, eutrophication (EUT) and abiotic depletion. Significant reduction was observed in PO, AC and EUT impact categories as a result of denitrification and desulphurization unit installation in coal-based power plants. Impact from transmission grid construction was found very negligible where impact from distribution grid was less than 4.5%.

Table 1 Portuguese power plants characteristics (average technologies) [14]

Fuel/energy source	Technology	Power (MW)	Efficiency
Coal	Boiler + steam turbine	300	36% (>2008); 37.5% (<2008)
Natural gas	Combined cycle (CC)	400	57.8%
Natural gas	CHP CC	80	40%
Natural gas	CHP gas engine	1.5	38%
Biomass	Boiler + steam turbine	10	16.5%
Biomass	CHP	12.8	34%
Hydro	Run-of-river	8.6	82%
Hydro	Reservoir	95	78%
Hydro	Mini-hydro	0.18	n/a
Wind	Onshore wind turbine	2	93%
Fuel oil	Boiler + steam turbine	500	35.6%
Waste incineration	Municipal waste incinerator	n/a	13%
Biogas	CHP gas engine	160	32%
Photovoltaic	Mix of technologies	n/a	n/a

CHP* = Combined heat and power

3.4 *Electricity Generation Through Clean Energy: LCA in China*

Over the next 50 years, electricity production and utilization will contribute to environmental degradation through large scale emissions, accounting hundreds billion tonnes of CO_2 [15]. Use of clean energy for electricity production has been recognized as the promising option for reducing GHG emissions. In China, nuclear energy, hydro-electric energy, and wind power are the leading clean energy sources as they produce substantially lower environmental impacts when compared to thermal power. Electricity generation through these three forms of energy results in fewer direct impacts on the environment during the operational stage. According to the Chinese policy, by the year 2030, the proportion of energy production through clean sources will reach up to 68%. However, from a life-cycle perspective, the potential indirect environmental impacts of these power technologies based on clean energy sources should not be overlooked.

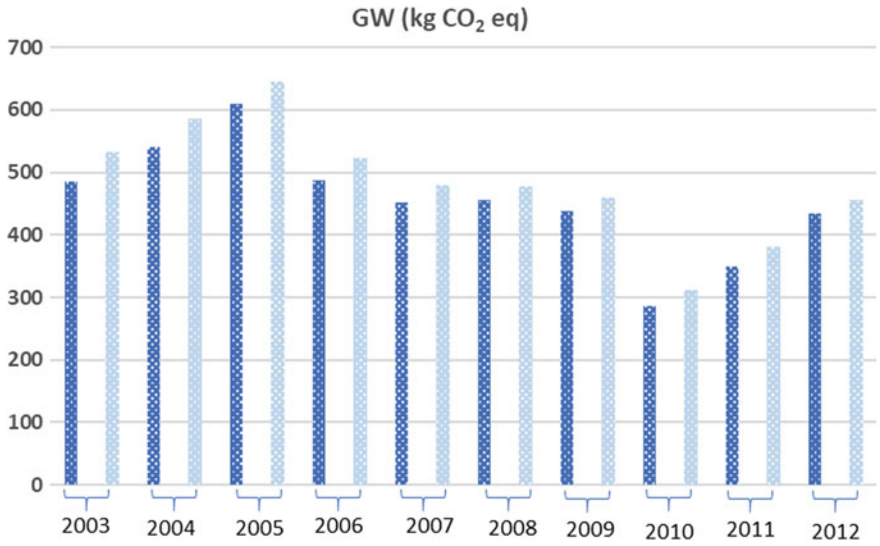


Fig. 4 Life-cycle global warming (GW) impacts per kWh of the Portuguese annual electricity generation and supply mix (2003–2012). The dark blue bars represent the GWP for electricity generation and the light blue bars represent the GWP for electricity generation and supply. Data has been retrieved from Garcia et al. [14]

Wang et al. quantitatively compared the potential environmental impacts of three power generation methods (hydro, nuclear and wind) including all the life cycle phases (manufacturing, construction, operation and decommissioning) [16]. For this study, 1 kWh of electricity generation was chosen as the functional unit. The assumed life span for hydropower facility and nuclear are 50% and 60%, respectively. In the hydropower case, the inventory analysis included the inputs of raw materials and energy which are primarily related to the production phase and construction phase of the hydro reservoir facilities. The electricity required for the operation stage of hydropower plants is consumed from the plants themselves, hence resulting in almost negligible emissions during the operational phase. For the nuclear power system, the inventory of the manufacturing phase is mainly branched into two components: supply of nuclear fuel and construction materials production. In terms of wind turbine, inventory of construction phase covered the installation of wind turbine and transportation (diesel fuel driven).

The potential environmental impacts from these three technologies for electricity generation has been assessed through CML 2001 impact assessment method (Fig. 5). SimaPro, a renowned LCA tool, has been employed for this assessment. The selected impact categories are global warming potential (GWP100), photochemical ozone creation potential (POCP), acidification potential (AP), human toxicity potential (HTP), eutrophication potential (EP). For simplification, this study has limited its scope for conventional emissions for above-mentioned power generation systems and

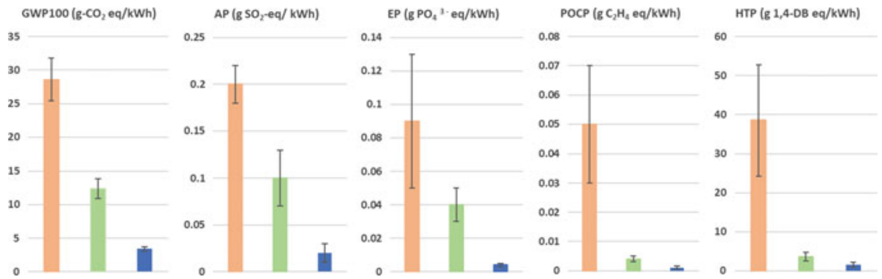


Fig. 5 Impact assessment results of three clean energy production systems (wind power [red bar], nuclear power [green bar] and hydropower [blue bar]). Data has been retrieved from Wang et al. [16]

the associated impacts to environment while the impacts from the unconventional emission such as leakage has not been considered.

LCA of these three clean power production technologies indicated wind power as having the highest environmental impact, which then followed by nuclear and hydro-based electricity generation. Details analysis of the unit processes showed the higher requirement of raw materials and energy inputs in the manufacturing phase for both wind and hydropower which contributed almost 50–70% in each selected impact categories. However, having major impacts from the manufacturing phase, wind and hydropower generated less environmental burdens in both the construction and operation phase. This detailed LCA analysis highlighted that more focus should be on the manufacturing phase to reduce the overall impacts of wind and hydropower. More specific material analysis through LCA showed the significant impacts of steel and concrete manufacturing process as these two elements are the core of wind and hydropower construction facilities. Therefore, LCA allows to investigate more on the specific material analysis which has the potential to reduce the impacts generating from steel and concrete and hence, can reduce the life cycle environmental impacts. On the other side of the coin, for the nuclear power, the major environmental impacts come from the decommissioning phase compared to the operational phase. Disposal of radioactive materials in decommissioning phase requires a huge quantity of electricity. Thereby, LCA of the nuclear power plant concluded the need for special attention for the nuclear fuel supply process in the manufacturing phase, as well as the decommissioning phase, to drop down the overall life cycle impacts on the environment.

Uncertainty analysis has been performed for this study using Monte Carlo Analysis through SimaPro. The main analysis discussed above did not consider any recycling feature. Hence, in the uncertainty analysis, recycling rate for wind power has been analyzed as the manufacturing phase found responsible for significant environmental impacts (Table 2). At 80% recycling rate, the GWP for wind power showed around 65.3% decrease compared to the no recycling case. Similarly, for AP, EP, POCP and HTP 80% recycling resulted 0.086 g SO_2-eq/kWh, 0.027 g $PO_4^3 -$ eq/kWh,

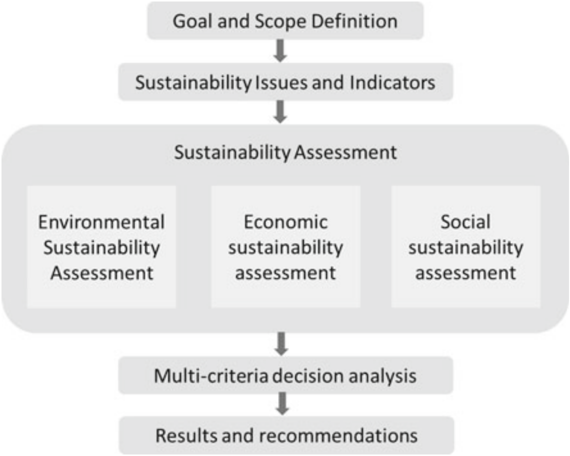


Fig. 6 Methodological format of life cycle sustainability assessment for Turkish Electricity Mix [32]

Table 2 Sensitivity results summary for wind power LCA [16]

Rate (%)	GWP100 (g CO_2 eq/kWh)	AP (g SO_2 eq/kWh)	EP (gPO_4^{3-}eq/kWh)	POCP (gC_2H_4 eq/kWh)	HTP (gDCB-eq/kWh)
0	28.56	0.20	0.094	0.016	38.41
20	18.27	0.15	0.064	0.011	29.81
40	16.24	0.13	0.053	0.010	24.28
60	13.17	0.11	0.040	0.0079	18.18
80	10.09	0.086	0.027	0.0056	12.09

0.0056 g C_2H_4 eq/kWh, 12.09 g 1,4-DB eq/kWh, respectively. Hence, this analysis highlighted the recycling rate is a sensitive parameter for this LCA study.

4 LCA and LCEA for Energy Use in Buildings: Energy Demand Prospective

With the economic development all over the world, several buildings are being constructed continuously for residential, office and commercial purposes. Right from the starting of the construction till demolition, buildings require high amount of energy. Worldwide, buildings consume 30–40% of total primary energy and thus responsible for 40–50% GHG emissions [17]. More specifically in the entire life cycle, conventional residential buildings consume 150–400 kWH/m^2 yr of primary energy while the commercial buildings, in particular office buildings, consume 250–550 kWh/m^2 yr of primary energy [18]. In this respect, LCA is now a renowned versatile tool which allows the reduction in building's energy consumption and associated GHG emissions [19]. This useful tool has added the most suitable environmental friendly measures for the building environment sector from a global perspective [20].

In buildings life cycle, the demand for energy has been classified as direct and indirect (or embodied). In simple words, energy used in construction, operation, renovation and demolition can be defined as the direct consumption of energy while the energy used in materials production used in building construction can be defined as embodied energy consumption [21]. Apart from the LCA, life cycle energy analysis (LCEA) has been appeared as a unique life cycle-based approach to examine all the energy inputs for a product or process. The following section will elaborate on the application of both LCEA and LCA in building environment from the energy demand perspective.

4.1 Life Cycle Energy Assessment (LCEA) in Building Environment

LCEA is considered as the simplified form of LCA. LCEA does not aim to replace LCA but aims to help in decision-making process for energy-related process or energy efficiency. Compared to the complete LCA, LCEA accounts only energy-related inputs at different life cycle stages for any product or process. This assessment accounts not only for direct energy required for the manufacturing process, but also considers the indirect/embodied energy required to produce any element, service necessary for the manufacturing process, thus allows more detailed energy analysis attributable to the building environment [22, 23]. The energy consumed directly in each life cycle phase (construction, operation, renovation, and demolition) of a building is clearly definable as well as measurable. However, it is way more difficult to measure the indirect energy required to support these main processes. In short, a building's LCEA accounts for initial and recurrent embodied energy, operational energy and demolition energy, covering the whole life cycle. Hence, it is considered as one of the powerful decision-making tools and often used at the building design stage to reduce the net energy consumption over the expected life cycle of the building. The detailed energy assessment is discussed below.

4.1.1 Embodied Energy

Embodied energy can be defined as the energy content of all the elements that are used in the building construction process and technical installation. This energy not only includes the new construction energy, but also the energy incurred during the renovation. But what does it mean by energy content of the material? It means the energy used in the process of raw material extraction, manufacture and then transfer of the material to the building construction site. Two types of energy combine in the embodied energy section: initial and recurring embodied energy. Energy incurred in the initial construction process refers to the initial embodied energy while energy incurred in the building repair and any material replacement process refers to recurring embodied energy. Ramesh T. et al. has expressed the life cycle energy as follows (Eq. 1–5) [18]:

$$\mathrm{EE}_i = \sum m_i M_i + E_c \tag{1}$$

where,

EE_i Initial embodied energy
m_i Quantity of material (i)
M_i Material (i) energy content/unit quantity
E_c Energy used at site for erection/construction of the building.

$$\mathrm{EE}_r = \sum m_i M_i \left[\left(\frac{L_b}{L_{\mathrm{mi}}} \right) - 1 \right] \tag{2}$$

where,

EE_r Recurring embodied energy
L_b Building life span
L_{mi} Material (i) life span.

4.1.2 Operating Energy

Energy used during the operational phase of buildings refers to the operating energy which includes energy for space heating and cooling purpose (such as for HVAC systems), hot water systems, lighting, running appliances and for cooking. The following equation defines the operating energy of buildings:

$$\mathrm{OE} = E_{\mathrm{OA}} \tag{3}$$

where,

OE Life cycle operating energy
E_{OA} Annual operating energy.

4.1.3 Demolition Energy

Energy used for demolishing buildings after the life span and transporting the waste materials from demolishing activity to the disposal site or recycling site is known as demolition energy. The demolition energy is expressed as follows:

$$\mathrm{DE} = E_D + E_T \tag{4}$$

where,

DE Demolition energy
E_D Energy used in demolishing activity
E_T Waste materials transportation energy.

All these embodied energy, operational energy and demolition energy together forms the life cycle energy (LCE) of a building over the life cycle, and thereby expressed as follows:

$$\mathrm{LCE} = \mathrm{EE}_i + \mathrm{EE}_r + \mathrm{OE} + \mathrm{DE} \tag{5}$$

However, in literature each study has modified the LCEA equation based on the scope of their studies. Utama et al. investigated the life cycle energy (LCE) of typical houses in Indonesia [24]. Initial and recurrent embodied energy and operational energy have been considered in the analysis of LCE in this study. The demolition energy has been excluded in this case. For the clay-based housing, the LCE was found 692.3 GJ, whereas for the cement-based enclosure this value was 732.8 GJ, indicating better LCE performance of clay-based enclosure. The detailed energy analysis indicated the higher embodied energy for clay-based enclosure as firing process in material production consumes much high energy as well as a high amount of mortar building. However, embodied energy contributed 9–14% of the total LCE, which indicates high operation energy. Moreover, this study also stressed that it is not necessary that materials having low initial embodied energy will automatically show low LCE as the material thermal properties have a significant influence on LCE.

4.2 *Life Cycle Assessment for Building's Energy Use*

In China, building embodied energy has been investigated through input-output based hybrid LCA [25]. Hybrid LCA is a unique combination of process-based LCA and input-output LCA which enhances the accuracy of LCA results as well as ensures complete boundary analysis. The estimated building embodied energy was 1.3528×10^9 t coal eq. for the year 2010. The manufacturing process of the non-metallic mineral product was indicated as having the most energy intensive flow, followed by the smelting and pressing of ferrous metals. From the hybrid LCA results for building embodied energy, this study has suggested the promotion of energy savings in the material production (especially for cement, steel clay brick and aluminum) through technical progress and introducing high performance materials. The low-energy house is one of the emerging sustainable building design concepts which is playing a significant role in the context of climatic protection and energy efficiency in the building environment. To investigate the environmental impact of low-energy housing, A. Audenaert et al. conducted a study in a single building (consists of 19 flats) using LCA [26]. Detail environmental impact assessment through Eco-indicator 99 method highlighted that production of materials generated the largest impact on the final eco-score. Hence, they suggested to consider the choice of materials as a key factor in reducing the environmental impact of the building sector. For instance, the authors indicated the potential of reducing impact by nearly 4.5% in the production phase through optimization of non-bearing materials. The next study discussed here aimed to reduce the LCE and carbon intensity in design phase using LCA for a medium rise office building in the UK [27]. Analysis of the LCE concluded 10.5 times higher operational energy compared to the embodied counterpart. For the embodied energy, structural materials contributed the most. where reinforced concrete slabs alone contributed nearly 43% of total embodied energy. Design modification through LCA resulted in 13.4% saving for LCE, and hence concluded the benefit of applying LCA on the early design stage to reduce the LCE and associated environmental impacts.

5 Life Cycle Sustainability Assessment of Energy Systems

For the comprehensive sustainability assessment of the energy systems, integration of all three sustainability aspects (environment, economy and social) is critical. Hence, life cycle sustainability assessment (LCSA) of energy systems adopted life cycle thinking approach and included economic, environmental and social indicators. Thereby, LCSA has several similar characteristics as of the existing LCA and additionally combined economic LCA or, life cycle costing (LCC), and social life cycle assessment (SLCA) with environmental life cycle assessment (LCA).

$$\mathrm{LCSA} = \mathrm{LCA} + \mathrm{LCC} + \mathrm{SLCA} \tag{6}$$

The features of LCA has already been discussed above in Sect. 2. This section will elaborate the role of remaining LCC and SLCA for energy system assessment.

5.1 Life Cycle Costing (LCC)

LCC is a popular approach for economic aspects in LCSA of energy systems. While LCA tracks all environmental flows of any product or process throughout the life cycle, LCC only accounts the monetary input and output [28]. According to the Society of Environmental Toxicology and Chemistry (SETAC), LCC of any product or system is the combination of all economic costs throughout the life cycle of an energy system or technology which has been presented simply as follows [29]:

$$\mathrm{LCC} = \mathrm{C}_C + \mathrm{C}_{\mathrm{FO}} + \mathrm{C}_{\mathrm{VO}} + \mathrm{C}_W + \mathrm{C}_E + \mathrm{C}_T \tag{7}$$

where, C_C is capital cost; C_{FO} is fixed operating cost; C_{VO} is variable operating costs; C_W is waste management cost (recycling included); C_E is end-of-life disposal cost; and finally, C_T is transportation cost.

5.2 Social Life Cycle Assessment

Among the three aspects of LCSA, SLCA is a relatively young concept and the inclusion of SLCA in the sustainability practice is often marginal compared to the rest two dimensions. Similar to the environmental LCA, SLCA aims to assess product or process considering social value. SLCA has been defined as the social impact assessment process which assesses the social aspects of products or processes, and quantifies both positive and negative social impacts of products along its life cycle starting from raw materials extraction to final disposal [30, 31]. According to the United Nations Environment Program (UNEP) and Society of Environmental Toxicology and Chemistry (SETAC) guidelines, social impacts have been defined as outcomes of either positive or negative pressure on social endpoints/social relations as a result of activities by any stakeholders. It is not the aim of SLCA to indicate whether manufacturing of a material should be done or not, however, during the decision or design phase of production SLCA gives elements of thought.

5.3 LCSA Case Study

In turkey, electricity consumption is growing rapidly where electricity grid mix is mostly dependent in coal and natural gas (account 73% of total). To evaluate the LCSA of Turkish Electricity sector, as well as to find the most sustainable electricity production option, study has been performed in the year 2016, including 20 life cycle sustainability indicators (LCSI) (Table 3) where in total 516 power plants in Turkey have been assessed [32].

Similar to the previously discussed functional unit in environmental LCA, 1kWh electricity production in Turkey served as the functional unit for this “cradle to grave” LCSA study. Figure 6 represents the methodological format of this LCSA study for Turkish electricity mix. For environmental sustainability assessment, LCA tool GaBi V.6 and GEMIS 4.8 have been employed and LCIA method CML 2001 has been followed for quantification of impacts following the ISO 14040 and 14044 guidelines. Environmental issues related to power production such as climate change, emissions to air, soil and water, and resource depletion has been considered in this case which are translated into 11 environmental indicators listed in Table 3. For the economic assessment, 3 indicators have been considered associated with electricity cost: capital cost (construction cost), annualized cost (annual cost for operation) and levelized costs (lifetime average cost). For the social assessment, 3 social

Table 3 LCSA indicators studied in Turkish electricity assessment [32]

Sustainability aspects	Sustainability indicators	Units
Environmental	Abiotic resource depletion potential (elements)	kg Sb eq./kWh
	Abiotic resource depletion potential (fossil fuels)	MJ/kWh
	Global warming potential	kg CO_2 eq./kWh
	Acidification potential	kg SO_2 eq./kWh kg
	Eutrophication potential	kg PO4 eq./kWh
	Fresh water aquatic ecotoxicity potential	kg DCB* eq./kWh
	Human toxicity potential	kg DCB eq./kWh
	Marine aquatic ecotoxicity potential Ozone	kg DCB eq./kWh
	Ozone layer depletion potential	kg CFC-11 eq./kWh
	Photochemical oxidants creation potential	kg C2H4 eq./kWh
	Terrestrial ecotoxicity potential	kg DCB eq./kWh
Economic	Capital costs	US$
	Total annualized costs	US$/year
	Levelized costs	US$/kWh
Social	Direct employment	Person-years/TWh
	Total employment (direct/indirect)	Person-years/TWh
	Injuries	No. of injuries/TWh
	Fatalities due to large accidents	No. of fatalities/TWh
	Imported fossil fuel potentially avoided	Kg oil eq./kWh
	Diversity of fuel supply mix	Score (0–1)

DCB*: Dichlorobenzene

issues (employment provision, energy security, and safety of workers) are considered which then translated into 6 indicators. In the next step, multi-criteria decision analysis (MCDA), more specifically the multi-attribute value theory (MAVT), has been applied in order to integrate the environmental, economic and social aspects of sustainable assessment and facilitate identifying the best sustainable option for electricity mix in Turkey.

The findings from the LCSA indicated highest percentage of environmental impacts from fossil fuel operations. In terms of GWP, hard coal was found as the worst option emitting 1126 g CO_2-eq./kWh where the power production by small reservoir (4.2 g CO_2-eq./kWh) and run-of-river hydropower (4.1 g CO_2-eq./kWh) resulted in lowest emissions. Detail economic assessment resulted in the total capital cost as 69.3 billion USD of which hydropower plants accounted 43%. Social assessment concluded that the power sector in Turkey offers nearly 57,000 jobs, however, lower energy security as a result of dependence on imported fuels. Integrating all the assessment results through MCDA, the ranking of the power production options revealed hydropower as the most sustainable option. Hydropower remains the best option when the environment aspect is given the highest priority. Similarly, when the economic aspect becomes the priority, large reservoir-based power plant scores as the best option, while in case of prioritizing social aspect, run-of-river ranked first. Considering all the three sustainability pillars, fossil fuel-based power production options were found as least sustainable, hence suggested more efficient technologies for fossil fuel based power production.

6 Conclusion and Final Remarks

Sustainable development in the energy sector is critical as it acts as the foundation for most of the other sectors in this current world. Compared to the other sectors, more vigorous attempts have been taken till now to reduce the environmental impacts, especially GHG reduction, of the global energy sector. Hence, technological progress in energy field is mostly driven by cost and carbon emission value, however, it will be undesirable if we neglect the overall factors of energy systems. In this context, life cycle assessment (LCA) comprehensively evaluates the energy systems and helps to identify the possible scope for improvements to reduce not only the carbon emission, but also the overall environmental impacts. In line with the sustainable development goals, countries around the world have set their target to reduce the emissions from energy sectors and applying LCA for future energy policy. In this chapter, we have discussed three case studies for electricity generation from the energy supply perspective. To realize the other side of the coin, energy use in the building environment has been discussed from an energy demand perspective.

Along with the environmental aspects of energy systems, it is very critical not to lose sight of the other two aspects of sustainable development. Life cycle sustainability assessment (LCSA) provides the opportunity to evaluate a board range of issues related to energy systems, spanning the three sustainability aspects: environment, economy and society. By adopting a life cycle approach, LCSA helps to make holistic decisions and ensures avoid of problem shifting. Generally, the key elements of LCSA of energy systems are environmental LCA, life cycle costing of energy system/technology and social life cycle assessment. The importance of LCSA is increasing rapidly among the energy-related industries, policymakers in energy sector and governmental bodies. Hence, the role of LCSA in the energy sector is more important than ever to meet the United Nations Sustainable Development Goals 2030.

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Renewable and Integrated Renewable Energy Systems for Buildings and Their Environmental and Socio-Economic Sustainability Assessment

Shoukat Alim Khan and Sami G. Al-Ghamdi

Abstract The building sector has a significant contribution to global warming with direct or indirect emission of greenhouse gases, including CO_2, CO, N_2O, and CH_4. Residential sector building contributes 36% of the total CO_2 emission globally. The delocalized energy production and building with more sustainable design and low energy are the features that attract the project developers and architects to Renewable Energy Systems (RES). This chapter presents an attempt for the sustainability assessment of building-integrated renewable energy systems. The chapter identifies different RES used for onsite production of renewable energy for buildings' energy need and their environmental and socio-economic impacts. Solar, wind, geothermal, and biomass energy are the primary sources for standalone and onsite energy production in building sector. The selection of RES technology highly depends on the availability of the energy source and type of required energy. The fluctuation in availability of renewable energy sources and the diverse nature of the required energy for building makes integrated renewable energy systems more sustainable for buildings energy requirement. LCA is a standard assessment method considered by researchers for the environmental analysis of building-integrated RES, while economic impact assessment is performed by Life Cycle Costing (LCC). All energy systems, including renewable and non-renewable energy systems, have an impact on the environment. Energy is strongly associated with environmental problems ranging from local to global issues. This includes air pollution, carbon emissions, ozone depletion, etc. For industrialized and developing countries, these problems can be more severe if not properly integrated with infrastructure. The technological non-complexity and local applicability make the solar energy preferred choice for buildings' energy application. Solar energy is used both for the production of electrical and thermal energy. RES resulted in higher environmental sustainability with lower impact as compared to fossil fuels. However, the extent of impact strongly depends on variables like location and source of energy for the replaced energy system. Biomass-based system is the most economical system among the considered building-integrated RES. RES systems provide more job opportunity for the

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S. A. Khan · S. G. Al-Ghamdi (✉)
Division of Sustainable Development, College of Science and Engineering, Hamad Bin Khalifa University, Qatar Foundation, Doha, Qatar
e-mail: salghamdi@hbku.edu.qa

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equivalent spent on fossil fuels based system. However, higher installation cost, lack of expertise, high maintenance, and high capital investment are the critical barriers in its application. A case study presenting a renewable energy system for building different energy needs such as heating, cooling, electricity, and hot and cold water production is presented at the end of the chapter.

Keywords Renewable energy · Buildings · Socio-economic assessment

1 Introduction

Efforts are made to find more sustainable decisions for buildings due to their increasing energy demands [1]. Currently, residential buildings are responsible for 36% of the total CO_2 emission, with an exponential increase in recent years, hence considered as a suitable candidate for changes to be implemented towards a more sustainable environment [2]. According to the US Energy Information Administration, the predicted increase of energy in commercial and residential building is 1.5 and 1.1% annually from 2008 to 2035. This increase also predicted the development in living standards of society.

The delocalized energy production and building with more sustainable design and low energy are the features that attract the project developers and architects to Renewable Energy Systems (RES) [3]. The technologies with minimum or zero environmental impact are generally called green energy technologies. The comparison of advantages of clean energy is the critical factor to consider for the policies and strategies of its implementation.

RES can be installed onsite for energy production with a significant contribution to energy consumption. Leading international companies in the construction sector report the utilization of renewable energy as a critical feature in their sustainability reports. Besides, renewable energy plays a critical role in mitigating the increasing concern of the public on environmental pollution.

For energy systems with an increased level of sustainability meets the following criteria [4]:

(a) Ability to fulfill the current and future energy needs.
(b) Minimal or zero negative environmental and social impact.
(c) Preservation of natural resources.
(d) Preservation of water, land, and air.
(e) Zero or low emission of greenhouse gases and carbon.
(f) Generation of energy without affecting future generation necessities.

A rapid increase in RES in buildings have been observed globally during the last decade [5]. Renewable energy can be used for major energy consumption sources in buildings such as electrical energy for lightening and appliances, cooling, heating, and hot water. Residential and commercial buildings are two main categories of buildings.

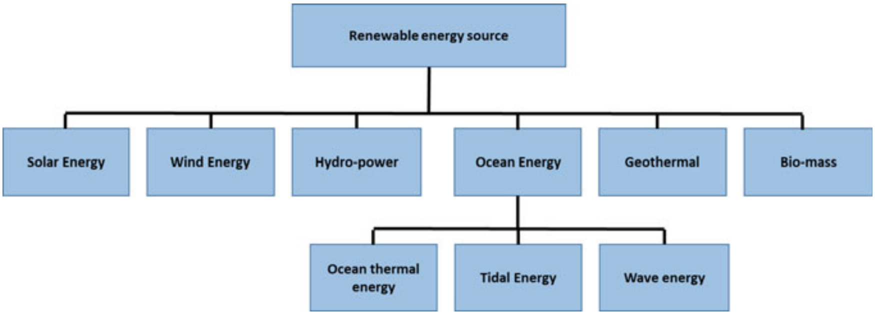

Fig. 1 Fundamental renewable energy system and its classification

The selection of RES technology highly depends on the availability of the energy source and type of required energy. Solar, wind, hydro, tidal, geothermal, Ocean (tidal, thermal, and wave), and biomass are considered the key and mature renewable energy technologies, so far, that are used for different applications. However, in the buildings sector, the solar, wind, geothermal and biomass energy are the primary sources for standalone and onsite energy production (Fig. 1).

This chapter presents an attempt for the sustainability assessment of building-integrated renewable energy systems. The chapter identifies different RES used for onsite production of renewable energy for buildings' energy need and their environmental and socio-economic impacts. Following the introduction part, Sect. 2 summaries different building-integrated RES and their contribution and an introduction to integrated RES and towards net-zero energy building. Section 3 focused on the environmental, social, and economic sustainability of building-integrated RES. A case study presenting a renewable energy system for building different energy needs such as heating, cooling, electricity, and hot and cold water production is considered in Sect. 5, followed by the conclusion section.

2 Building-Integrated Renewable Energy Systems

2.1 Conventional and Renewable Energy Systems

Several energy resources, a form of energy that can be transformed into another form of energy, are available on earth such as fossil fuels, renewables, nuclear, waste, and others. Conventional energy techniques use fuel with severe environmental implications. For example, coal power plants produce a considerable amount of particulate substance, carbon dioxide, and contaminants to water, ground, and sky. Similarly, electricity production through fossil fuel is highly polluting technique. Natural gas, coal, and oil are considered as fossil fuels typically. However, oil sands, coalbed, and shale gas are recently explored and available fossil fuels.

The conversion efficiency of any energy represents its quality. Among the conventional energy resources, natural gas has the highest quality Renewable energy resources usually have low conversion efficiency. Electricity is considered as the highest quality form of energy. The direct conversion from source to electricity is considered the primary advantage of solar photovoltaics [6, 7]. Among renewables, biomass has the highest quality due to the production of high-temperature gases. However, wind and solar energy can easily scale-up and scale-down.

The increasing demand for energy and severe environmental impacts of current energy resources has increased the importance of replacement of conventional energy resources with RES in the building sector. Existing power plants are the primary source of electrical, cooling, and heating energy in buildings. Coal, natural gas, and oil are commonly used for 75% of total electrical power production in these plants, globally [8]. Nuclear energy is used for power production of only 6% of total power production. In renewable energy systems, hydropower is the most established form of renewable energy systems that are used for 16% of power generation.

2.2 *Renewable Energy Systems for Buildings*

Renewable energy like wind, solar, geothermal, and biomass have significant potential to apply for buildings' energy need. Solar-based RES have gained remarkable attention and applied as photovoltaics system, hybrid photovoltaic thermal, and solar thermal water heating systems in buildings. Building-integrated wind energy is commonly applied in high rise-buildings for electrical power generation. Geothermal is widely available, and heat pump technology has high potential to use this form of renewable energy for buildings. Similarly, biomass, containing firewood, livestock manure, crop straw, and municipal and organic waste can be utilized for building heating either by direct combustion or by the generation of biogas. Biogas, from livestock manure, is generated by biochemical conversion [5].

2.2.1 Building-Integrated Solar Energy

Solar energy is the key for most of the renewable energy resources. The evaporation of water from sea, lakes, river, and other sources by solar energy is the key to rain cycle, which resulted in hydropower. Photosynthesis is caused by solar energy which later becomes the source of biomass. Solar energy causes a difference in temperature between different locations, which resulted in a wind stream for wind energy. Similarly, the difference in temperature due to the sun and location of the sun results in tidal waves. Therefore, it is more feasible to convert solar energy into a useful form of energy using different energy systems and devices. The intensity and spectrum of solar irradiation determine the performance of any solar system.

The technological non-complexity and local applicability make the solar energy a preferred choice for buildings' energy application. Solar energy is used both for the production of electrical and thermal energy. Electrical energy can be directly used cooling, heating, and other electrical requirements of the building. At the same time, thermal energy can be directly used for hot water and heating purpose of the building. The technology can be applied both in the design stage or utilization of the building. Technologies like solar thermal absorption cooling system can be used for cooling purpose of the building in the areas with high cooling demand of the building. The placement of solar absorber for hot water production is the simplest and effective way for hot water production in buildings. The technology can upgrade for heating of the building and getting popularity in many European countries, recently.

Solar energy for building cooling and heating can be either active or passive system. The passive solution is generally related to the design stage, which consists of various techniques to store, collect, distribute, and control solar energy. Several techniques are also used to optimize thermal comfort by enhancing the natural transfer of sunlight and stored energy [9]. For example, for cold regions, the building is designed with maximum exposure of ceiling, windows, and walls for absorbing sunlight. Sun ceiling/ sun, wall surface, and south opening are some of the standard techniques for passive solar heating.

Similarly, in cold regions, the windows' openings towards the south are kept larger than the other side to maximize the heat gain in the winter season. Night insulation is suggested for buildings in winter and sun protection for the summer season. Similarly, the sealing opening is recommended on the south side of the building that is covered by other structures, with special care of insulation for these openings in summer.

Active systems rely on external mechanical equipment to use solar energy for the building. Photovoltaics panel, air–water collector, and other efficient collectors are an example of such solar systems. Solar heating systems are commonly active systems. In this system, solar energy is collected and stored in the storage tank placed either inside or near the building; the energy is then pumped to the building using external electrical energy. Hot water is the typical fluid used in these systems for the transportation of thermal energy. Similarly, absorption cooling using solar energy is another example of an active solar system.

Both active and passive heating systems used for building heating and cooling are environmentally friendly. Due to the availability of solar energy, solar energy systems are more suitable for non-residential buildings with working hours in the daytime.

2.2.2 Building-Integrated Wind Energy

The installation of the wind turbine system for buildings energy need is an essential application of wind energy. The system is practiced for both onsite and off-site energy generation for building energy need. Developed countries like Netherland, Britain, and Sweden started practicing its generation in high buildings since 2001 [5]. Similarly, China has installed small-scale wind turbine on a large-scale during recent prompt urbanization. Similar to solar, wind energy also helps in lowering the investment cost and transmission cost due to onsite generation. Wind energy can be used, both for the generation of electrical and thermal energy. The generation of electrical energy using wind turbine is a more common and advanced technique.

Wind energy is worth mentioning renewable energy technology with decreased levelized cost and rapid growth in recent years. The difference in temperature between the two regions causes wind stream to flow. The mechanical energy of wind stream can be converted to other forms using an appropriated machine. The wind turbine is used to convert the kinetic energy of wind to electricity. The theoretical limit of wind energy conversion is 59.3%, as calculated by Albert Betz [10]. However, the current technologies of wind turbine reach from 35 to 50% of efficiency [11]. Due to its wide range of availability, wind power plants have been constructed around the globe.

The wind turbine can also be used to convert the mechanical energy to other forms such as pumping, wood cutting, and thermal energy generation. However, similar to solar energy, the fluctuation in the intensity of wind energy throughout the year is one of its limitations. Hence, the storing of the available wind energy, such as in the form of generated electricity or heat, is essential for its successful implementation. The energy can be stored as chemical energy (hydrogen), electrochemical energy (batteries), kinetic energy (flywheel), etc.

For built environment application, the small-size wind turbine is currently under research with a particular interest in its decentralized power generation ability. These turbines are preferred to install on top of the building [3]. The zero-velocity height in urban areas is at a certain height, which is a function of the average height of the nearby buildings. However, the wind profile in urban areas with the high building is usually very complex, and hence the real production predictability is still under testing phase. However, some general principles are reported in the literature, such as the installation building for wind turbine should be higher than the average height of the surrounding buildings.

Several other effects are needed to be considered due to the negative effect of wind turbines on buildings, including [12]:

(a) Architecture difficulty to integrate wind turbine to building due to involved principles of wind turbines installation for optimal output.
(b) The turbulent flow created by buildings and other obstacles in urban areas affects the working of wind turbines.
(c) The end of the wind turbines blades is dangerous for flying animal.
(d) The produced low-frequency noise might affect the residents or working people nearby.

2.2.3 Building-Integrated Geothermal Energy

In buildings, geothermal energy is mainly used for space cooling and heating using heat pump technology. The technology uses the earth as a heat source in winter for building heating and heat sink in summer season to remove heat for building cooling. The technology is used both in developed and developing countries with a particular focus on new buildings. For example, in China, the technology is continuously increasing in buildings with more than 160 heat pumps [5]**.** The technology can save from 30 to 70% of the required energy for space heating and cooling in buildings [5].

Geothermal heat pump got popular in the 1950s after the installation in common wealth building, in Portland. The system is then replicated in many institutional, complexes, and commercial buildings. Compare to other technologies; geothermal heat pumps still have a minimal contribution in HVAC systems due to already developed technologies. The lack of expertise and high maintenance cost are some of the other reasons.

In addition to standalone RES, geothermal systems are widely used in integration with solar energy for buildings' energy needs. For example, the integration of solar photovoltaics and a geothermal system, for electrical and thermal energy requirement of the building. Similarly, the integration of geothermal systems with the solar thermal collector for efficient heating of the building. Sarbu and Sebarchievici [13] conducted a detailed review of the use of ground-sourced heat pump systems for the cooling and heating energy demand of buildings.

2.2.4 Building-Integrated Biomass

Photosynthesis is considered a primary source of biomass. Wood, grass, cane, straw, charcoal, manure, wastepaper, and domestic waste are few sources to mention for biomass. Both biogas and direct combustion approach are used for buildings energy application. Biomass is also used for electricity production using power plants. Rahman et al. [14] studied the design and its environmental effect for power plants of 115 kW to meet the electricity requirement of the entire residential building. The technology is specifically more useful for rural areas. The construction of biogas facilities in rural areas and the regulation mechanism is highly under consideration in countries like China[5]. Besides, biofuels are the economically favorable alternative for buildings energy as compared to fossil fuels.

Biomass contains chemical energy with typically high heating value commonly between 4 and 30 MJ/kg. The biomass can be directly used for energy generation using techniques like combustion or can be used for the production of biofuels. These fuels can be burned to produce high quality/temperature thermal energy.

2.3 Integrated Renewable Energy Systems for Buildings

The fluctuating and intermittent nature of solar energy can be reflected in its secondary renewable sources such as wind, hydro, and ocean. The fluctuation in availability of renewable energy sources and the diverse nature of the required energy for building makes integrated renewable energy systems more sustainable for buildings energy requirement.

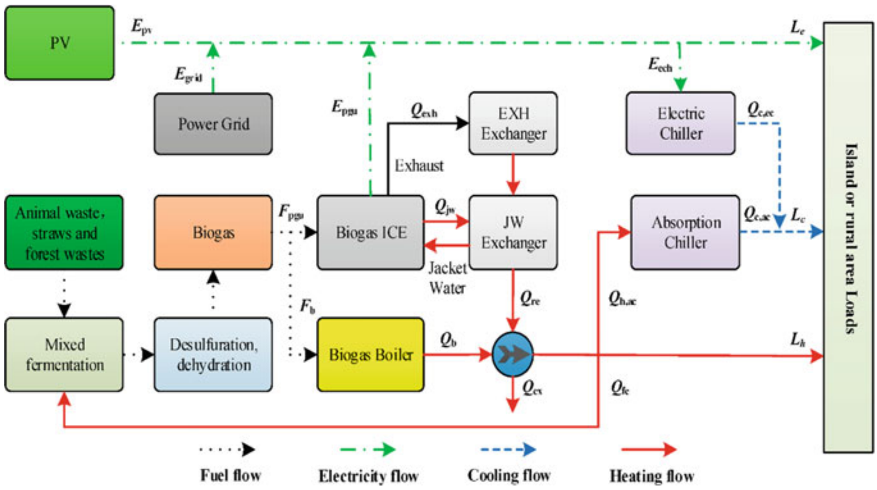

Fig. 2 Solar and wind energy integrated system for heating, cooling, and power requirement of buildings [19]

In order to reduce this fluctuation in availability of energy, different renewable energy systems can be integrated for a more stable energy system. Another reason for the integration of renewable energy systems is the multigeneration energy requirement. In an integrated renewable energy system, different renewable energy systems are integrated to fulfill different energy requirements at the same time. For example, solar and wind energy can be coupled together for different conditions including, the availability of electrical energy through the day and night, availability of electrical energy during adverse weather conditions, and fulfilling both electrical and thermal energy requirements of buildings. Similarly, geothermal heat pump and solar energy can be coupled to fulfill the electrical and HVAC requirement of the building.

It is worth to note that the integration of the renewable energy system is highly dependent on the nature of the required energy and the availability of different renewable energy resources. Different examples of such systems can be found in the literature [15–18]. Figure 2 represents the design of the solar and biomass integrated multigeneration system for heating, cooling, and power requirement of buildings [19]. Integrated renewable energy systems also provide an efficient solution for renewable energy-based net-zero energy buildings.

2.4 RES Towards Net-Zero Energy Buildings

For buildings, environmental problem and energy crises net-zero energy buildings (NZEBs) are widely accepted as a promising way out [20]. A range of different countries has already provided its supportive policies and financial incentives for

NZEBs. For example, the goal of “nearly net-zero energy buildings” has been set for all the buildings in Europe from 2020 [20]. Similarly, the California Public Utilities Commission has set “net-zero energy target” for all new commercial buildings by 2030 and all new residential buildings by 2020 [20].

Three approaches have been identified generally as a key factor for achieving the goal of NZEBs [20]:

(1) Passive design strategies such as building orientation and heating and cooling strategy
(2) Application of energy efficiency techniques, such as HVAC and energy-efficient appliances.
(3) Use of energy production technologies such as photovoltaics panel, wind power, combined heat and power, and combined cooling.

The classification of general approaches for NZE buildings is summarized in Fig. 3.

The integration of new technologies and carbon reduction targets have shifted the focus of research towards RES for NZEBs. The integration of RES provides an efficient way to meet the target of the diverse nature of the required energy for buildings. The selection of appropriate renewable energy technology and their integration to achieve the goal of nearly NZEBs is an exciting field and attracts many researchers. Few examples of such cases can be found in the literature [21–26]. Different passive and active renewable energy systems such as solar and wind geothermal are integrated into these studies.

The current studies are based on the ideal working performance of renewable energy systems ignoring the reliability and ageing of the systems. Hence have a lower probability of achieving this goal. Hence, the question of how reliable these systems are still under investigation [17].

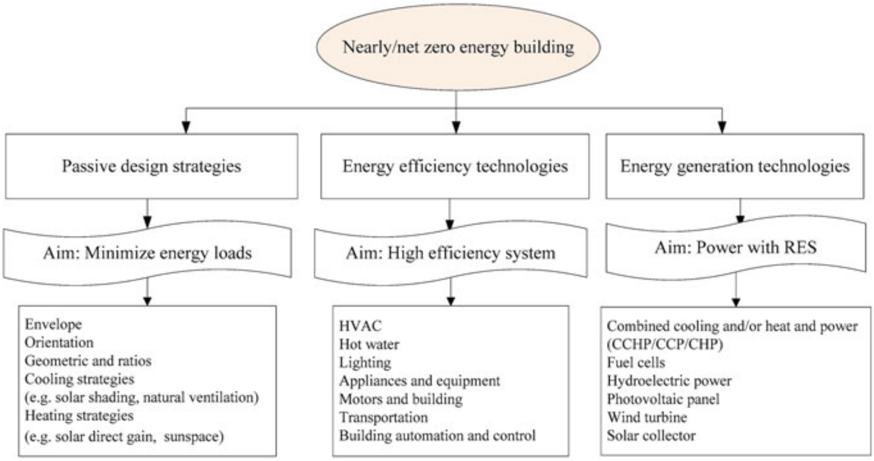

Fig. 3 Approached for NZEBs, the general classification [20]

3 Sustainability of Building-Integrated RES

This section of the chapter covers the environmental and socio-economic sustainability assessment of renewable energy systems for onsite energy requirement of buildings. The section is further divided into environmental and social and economic sustainability of RES for buildings. LCA is a common assessment method considered by researchers for the environmental analysis of building-integrated RES, while economic impact assessment is performed by Life Cycle Costing (LCC).

3.1 Environmental Impact of RES in Buildings

All energy systems, including renewable and non-renewable energy systems, have an impact on the environment. Energy is strongly associated with environmental problems ranging from local to global issues. This includes air pollution, carbon emissions, ozone depletion, etc. For industrialized and developing countries, these problems can be more severe if not properly integrated with infrastructure [8]. The power generation pollutes the air by producing contaminants and causes global warming and climate change effect. This could result in serious events such as sea level increase and heavy and acid rainfall and albedo effect.

The building sector has a significant contribution to global warming with direct or indirect emission of greenhouse gases, including CO_2, CO, N_2O, and $CH_{4.}$ Only residential sector building contributes 36% of the total CO_2 emission globally [2]. The exponential increase of this emission has underlined the importance of alternate and clean energy choices for energy demand globally.

Although not all renewable energy resources provide inherently clean energy, there are significant other reasons to encourage the shift from conventional to renewable energy systems [8] including:

(a) Although no energy resource is emission-free, renewable energy resources have a much less environmental impact.
(b) Unlike fossil fuels, renewable energy resources can supply sustainable energy without the depletion of energy resource.
(c) More sustainable energy supply is ensured along with decentralization, economical power supply and flexibility.

The integration of the renewable energy system into buildings provides a clean and comparatively more sustainable solution to this problem. However, the externalities of any renewable energy project, due to the utilization of other resources and goods, rise the environmental impact. Most of the environmental impact is associated with the manufacturing of the connected components. Life Cycle Analysis (LCA) is generally considered in the literature for the environmental sustainability assessment of these technologies [27–29].

Solar: Building-integrated solar systems are both used for thermal energy and electrical energy production [30–32]. The environmental effect of solar photovoltaics is studied by many researchers using both modeling-based and experimental-based approaches. Compared to photovoltaics, thermal systems are less explored for their environmental impact.

Researchers have reported several studies on the environmental impact building-integrated photovoltaic systems for residential buildings. The studies considered different installation locations, different cell materials and installation equipments. However, almost all the studies reported lower environmental impact of photovoltaics system during its life span as compared to conventional power production. CO_2 and embodied energy is the most studied environmental impact for different configurations and technologies of the building-integrated solar energy system; few studies also reported LCCA.

In general, building-integrated solar thermal systems have a high potential for environmental performance. The environmental performance of solar systems is better for regions with high solar radiation. Lamnatou et al. [33] presented a critical review of the environmental impact of solar systems with an emphasis on the building-integrated system, including both thermal and electrical systems. The study identified a gap of LCA study of the building-integrated solar system and their effect on LCA of building itself. In his study, Lamnatou et al. [34] investigated the environmental effect of building-integrated active solar thermal system. Considerable reduction in equivalent CO_2 from 28 to 96% is reported. Equivalent CO_2 reduction is reported to be strongly related to the adopted source of electricity in that region. The study also reported a considerable reduction in environmental impact by small modification in solar collector configuration.

The environmental impact of solar energy for domestic water heating (DWH) is analyzed by [35]. The study reported a considerable reduction in emissions. Compared to conventional electricity, the reduction in greenhouse gases is reported upto 80%. The system is analyzed with a backup system from the conventional electricity system. The system is considered with 79% energy contribution from solar.

Wind: Similar to solar energy, a significant proportion of building-integrated wind turbine is related to the manufacturing of the mechanical components. However, there is a huge environmental benefit of power production from the wind turbine. The recycling of wind turbine material could be considered as an important parameter to reduce its environmental impacts. The life cycle performance of the wind turbine depends on many factors including available wind resource, installed geographical position, and material used in its production. Compared to a rural area, the higher environmental benefit can be achieved in an urban environment.

Allen et al. [36] investigated the environmental impact of the micro wind turbine for building energy application. The study reported heavy metal pollution during the manufacturing phase of the mechanical components due to the use of metals like aluminum, steel, and copper and their processing. The overall impact of the system is reported positive, and enhanced environmental performance is reported with the sued of recycled materials.

This impact is added by the foundation, where the turbine is not installed directly on the building. Cement is reported as one of the principal components with the highest environmental impact in the turbine foundation. Similarly, compared to an onsite wind turbine for building energy needs, the offshore wind power generation is more environmentally friendly.

Geothermal: Studies have reported both high energy saving and environmental impact for this system [37]. Similar to solar and wind system, the significant environmental impact in the ground source heat pump system is the contribution from the manufacturing of the components. While in working condition, the significant contribution is the result of the mechanical pump used to circulate the working liquid in the loop between the ground and the building [37].

However, most of the analyses performed based on short-term experimental results and short-term impacts are discussed. It is essential to consider the long-term environmental and economic effect of these systems.

Biomass: The replacement of conventional fuels with biomass could result in a significant environmental performance. It results not only in reducing the environmental cost but also results in favorable energy rating for the building [2]. The environmental impact of biomass is sensitive to the location used and the fuel replaced. For example, the replacement of gasoil with biomass can decrease the CO_2 emission by 95%.

3.2 Socio-Economic Assessment of Renewable Energy in Buildings

The integration of RES for building energy needs is increasing due to the continuous decrease in prices. In the last decade, the prices of solar and wind system have decreased considerably. LCC is a commonly used method by researchers for the economic sustainability assessment of building-integrated RES. In solar energy, thermal systems generally result in a lower cost than the equivalent energy production by fossil fuels. However, photovoltaics system is generally more expansive [38]. Kalgirou [35] investigated the economic aspect of solar-assisted heating and hot water production for building and reported promising financial results with a payback period of 2.7 years.

Building-integrated geothermal heat pumps system generally results in the generation of more economical energy. Both environmental and economic impacts are reported positive by researchers [39, 40]. However, their maintenance cost can be higher in case of leaking of the heat exchanger. Besides, the capital cost is higher and required continuous energy external power for working. This contributes to the total maintenance cost. However, neglecting the uncertainty-related GSHP has high environmental and economic impacts. It is worth to note that the experimental study reported the economic feasibility is performed for the short-term period, and it is recommended to investigated long-term economic performance of these systems.

Compared to solar, wind, and geothermal systems, biomass is a more economical renewable energy source for building-integrated energy system. The economic saving reaches upto 70% for wood pellets and approximately 88% for olive pits and wood chips, compared to gasoil. Uncertainty analysis for RES is a critical aspect that is neglected in most of the research [20]. The systems are generally considered with ideal and constant output neglecting the ageing effect of the equipment and maintenance issues. This problem is common in system-level design and analysis, for example, the performance of NZE buildings or integrated RES.

Social: Although for building energy needs, conventional energy systems are more attractive choices than many RES; however, they severely affect the environment and social impacts. Renewable energy systems produce more jobs than the equivalent amount spent on fossil fuel power generation. The creation of job takes the life standard of the people beyond the economic benefits [41]. The integration of RES helps to diversify the economy by investing in a variety of available resources instead of focusing on two primary energy sources (oil and coal).

The social and environmental cost of RES and fossil fuels are in the opposite direction [41]. The prices of RES are more stable than the fluctuating oil price, hence, provides a constant energy price for the installed system, which results in both social and environmental costs. RES also help in mitigating the public concern on environmental pollution.

Social awareness, along with economic benefits, can contribute significantly to the implementation of building-integrated RES. Building-integrated RES provide a standalone distributed system for energy generation, which helps not only in preserving the clean environment of the remote location but also their social life and health.

4 Case Study: Building-Integrated Concentrated Photovoltaics System for Heating, Cooling, Hot Water, and Electrical Energy Requirement

The renewable energy systems are designed to fulfill the energy needs of buildings that can be classified in a single-source renewable energy system and integrated renewable energy system. The selection of types of the renewable energy system for any designed strictly depends upon the availability of renewable energy, the type of energy required, and economic feasibility of the source.

Figure 4 represents the schematic of single-source building-integrated renewable energy-based multigeneration system. The system is designed and analyzed for electrical energy, space heating and cooling, and fresh and hot water production. Concentrated Photovoltaic Thermal (CPV/T) system is used as a source of electrical and thermal energy. The overall system is divided into five subsections (i)–(v), Fig. 4.

Sunlight, reaching the CPV/T system is converted into electrical and thermal energy. The electrical energy is used for the electrical requirement of the building during the daytime. While the surplus energy is stored combined by Proton Exchange Membrane Fuel Cell (PEMFC). The electrical energy is first used in electrolysis to

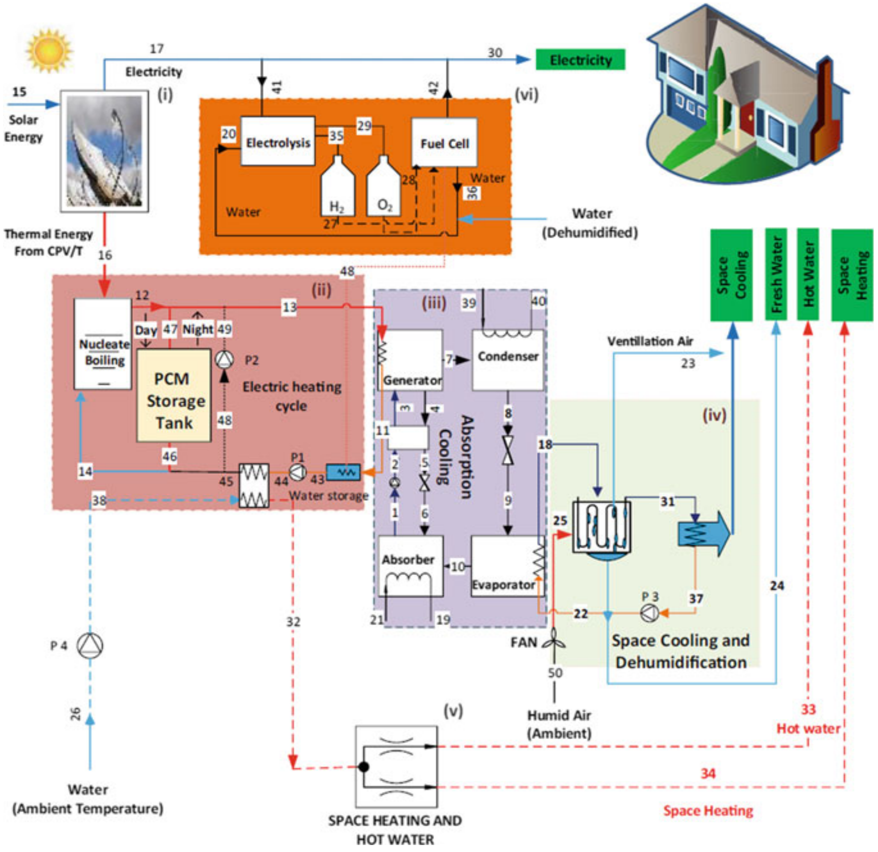

Fig. 4 Schematic of the proposed solar-based renewable energy system for electricity, HVAC, and space heating and cooling requirement of building [42]

generate oxygen and hydrogen during the daytime. At the nighttime the generated H_2 and O_2 is converted back into electrical energy by the fuel cell.

The thermal energy is extracted from CPV/T system using advanced Nucleate Boiling Heat Transfer (NBHT) system. A portion of this thermal energy is stored in Phase Change Material (PCM) based storage unit. At the same time, the remaining is used for building cooling during summer and heating during the winter season. The stored thermal energy is used during the nighttime and in case of the unavailability of solar energy such as cloudy weather. A water heater is designed to run on the stored electrical energy in case of unavailability of solar energy.

Absorption cooling system (iii) is selected to produce space cooling using thermal energy. Space cooling and dehumidification system (iv) is designed to produce cooling and freshwater production through humidity harvesting. The space heating and hot water production unit is used using the generated thermal energy from CPV/T for building heating and hot water requirement. At base case, the system is designed at steady-state and then optimized for different output by the parametric study of different variables. The designed system performed at overall 67.52% of efficiency and 34.8% of exergy efficiency. The system is analyzed for different Direct Normal Irradiance (DNI), relative humidity, ambient temperatures, and installed capacity to verify the designed system for different locations and weather conditions.

5 Conclusion

Due to increasing energy demands, building-integrated RES is considered as a suitable candidate for changes to be implemented towards a more sustainable environment. This chapter summarizes different building-integrated RES that can be applied to onsite installation. Solar, wind, geothermal, and biomass are the four major types of such renewable energy system which are either applied as a standalone system or their integration with other renewable, and non-renewable energy systems are performed for the design of more sustainable energy systems. Both active and passive techniques are applied to use building-integrated RES. The chapter includes an environmental and socio-economic assessment of these systems. LCA and LCC are the conventional methods applied for the environmental and economic sustainability assessment. All energy systems, including renewable and non-renewable energy systems, have an impact on the environment. However, for RES, the impact is more associated with the production phase of the required components of these systems. All the RES resulted in higher environmental sustainability with lower impact as compared to fossil fuels. However, the extent of impact strongly depends on variables like location and source of energy for the replaced energy system. Biomass-based system is the most economical system among the considered building-integrated RES. Although for building energy needs, conventional energy systems are more attractive choices than many RES; however, they severely affect the environment and social impacts. This system provides more job opportunities for the equivalent spent on fossil fuels based system. Higher installation cost, lack of expertise, high maintenance, and high capital investment are the critical barriers in its application.

There is a need for precise strategies and policy development to implement these strategies for clean energy implementation. For the RES in building sector some of the solutions can be encouraging RES, environmental awareness in public, removal of subsidization for fossil fuels, supporting RES technology in research and development and implementation, easy access to clean and efficient energy resources, promoting decentralized renewable energy resources.

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Review and Selection of Multi-criteria Decision Analysis (MCDA) Technique for Sustainability Assessment

Byomkesh Talukder and Keith W. Hipel

Abstract Multi-Criteria Decision Analysis (MCDA) follows a transparent and structured process for a decision making by considering multiple criteria, whereas sustainability assessment requires to manage and assess multidimensional indicators. Hence, the procedures of MCDA can be useful to assess sustainability. In this chapter, to understand the applicability of MCDA for sustainability assessment the concept, procedure, strength and weakness, and classification of MCDA as well as suitability and the steps require to follow in using MCDA technique for sustainability assessment are discussed. Two case studies of the application of MCDA techniques for sustainability assessment are shown and their advantage and disadvantage are presented with a direction of further research.

Keywords MCDA · Multi-criteria · Sustainability assessment · MAUT · PROMETHE

1 Introduction

Multi-Criteria Decision Analysis (MCDA) is a technique to assist with decision making in the presence of differing criteria [57]. According to Kenney [32], it is an approach that applies common logic to make decisions in the presence of multiple criteria. MCDA techniques are applied to real-world problems related to various socio-economic sectors, such as the water sector, agriculture, tourism, energy, environment, biodiversity and forestry [59].

MCDA is a well-known area of Decision Theory [61] in which decisions are made to reach the final objective under a set of decision-making options [21, 58]. Hipel [28]

B. Talukder (✉)
Dahdaleh Institute for Global Health Research, York University, 88 the Pond Road, Toronto, ON M3J 2S5, Canada
e-mail: byomkesh.talukder@gmail.com; byomkesh@yorku.ca

K. W. Hipel
Department of Systems Design Engineering, University of Waterloo, Centre for International Governance Innovation and Balsillie School of International Affairs Canada, Waterloo, Canada
e-mail: kwhipel@uwaterloo.ca

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Table 1 Comparison of MPSC and SPMC Decision Making

MPSC	SPMC
A set of decision makers, $\{DM_{i,}\ i = 1, 2, \ldots, n\}$	A set of criteria, $\{C_i\ i = 1,2, \ldots, n\}$
A set of states, $\{U_j, j = 1, 2, \ldots, m\}$	A set of alternatives, $\{A_j\ j = 1,2, \ldots, m\}$
A set of preferences, $\{P_{ij}\ j = 1,2, \ldots, m\}$, for $DM_{i,}\ i = 1, 2, \ldots, n$, over the set of states, $\{U_{j,}\ j = 1, 2, \ldots, m\}$	A set of evaluations, $\{V_{ij,}\ j = 1, 2, \ldots, m\}$, for C_i, $i = 1, 2, \ldots, n$, over the set of alternatives, $\{A_{j,}\ j = 1, 2, \ldots, m\}$

Source Adapted from (Hipel et al. [27]:1186) with permission

divided decision problems into Multiple Participant-Single Criterion (MPSC) and Single Participant-Multiple Criteria (SPMC) types. Most problems in the real-world context can be categorized as multi-criteria decision problems, as a single criterion is judged to be unsatisfactory to help in decision making for complex real-world problems [40]. A comparison of MPSC and SPMC is presented in Table 1.

Doumpos and Zopounidis [17] divided decision-making problems into two groups: discrete and continuous. A discrete set of alternatives is associated with discrete problems in which each alternative is described in terms of attributes. During decision making, these attributes work as evaluation criteria. In continuous problems, infinite alternatives are possible. In decision making, one can only outline the feasible region where the alternatives remain [17].

The process that is followed in making a final decision by applying MCDA is called a problematic. In a discrete decision-making challenge, there are four main kinds of problematics: (i) choice, (ii) sorting, (iii) ranking and (ii) description [17]. See Fig. 1.

MCDA has become a specialized subject in the field of Operations Research (OR), which was initiated by the British Royal Air Force around 1937 to study the network of radar operators and how the judgments they made influenced the results of their radar operations [63]. MCDA is also one of the prominent fields of Management Science [34]. MCDA techniques have been exhaustively described and reviewed by many authors (e.g., [4, 17, 24]. The detailed theoretical underpinnings of different MCDA techniques can be found in Belton and Stewart [4].

1.1 MCDA Procedures

At present, many software programs have been developed to carry out MCDA analysis. In short, the MCDA technique usually takes a four-step procedure. The objectives are defined in the first step. In the second step, the decision criteria are selected based on the objectives to specify the alternative decisions. After deciding on the criteria and the alternatives, in the third step, the units of the criteria are normalized and weights are given to the criteria to reflect their relative value in decision making. The last step is to select and apply a mathematical algorithm to rank each alternative [25]. Table 2 gives more detail about each step.

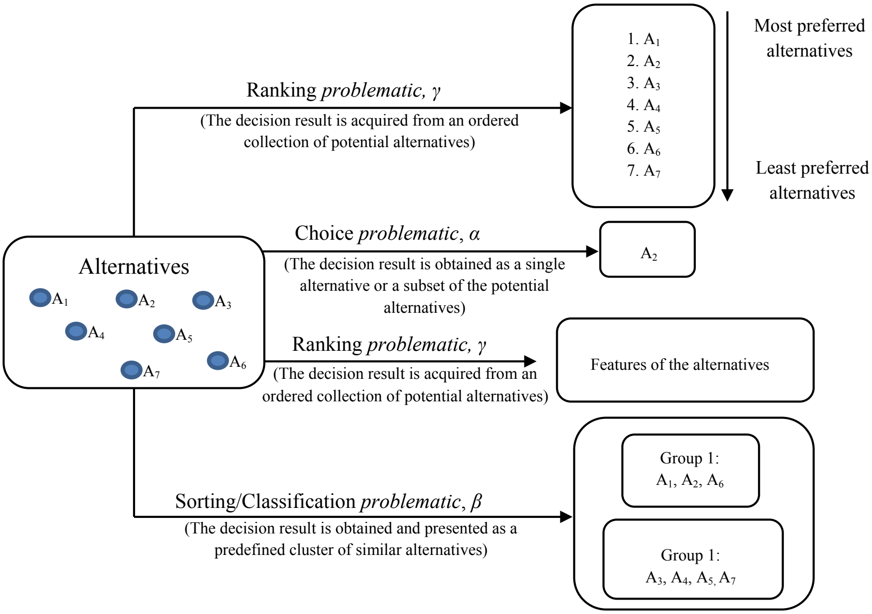


Fig. 1 Decision-making problematics with definitions. *Source* Adapted and modified from [17] with permission

Table 2 Steps in MCDA techniques

Step One: Structuring the decision problem In structuring the decision problem, stakeholders identify the issue about which they want to make a decision. Based on the decision problem, the objectives and the criteria are identified and verified
Step Two: Formulating criteria preferences and modeling To include the preferences of the criteria in decision making, the preference functions are identified. The preference functions can be either proportionate score or utility value
Step Three: Combining alternate assessments (preferences) The MCDA technique is used to evaluate and compare the alternatives based on the requirements of the decision. The selected criteria for decision making are weighted according to the relative importance of stakeholders or objectives of the decision making. Either linear or additive functions are applied for weighting; the weighting can be subjective, objective or a combination of both. The final decision is made based on the best score generated from the weighted average
Step Four: Recommendations After making a decision based on the best score, the recommendations are put forward and guidelines are developed for further examination

Source Based on Vansnick [64], Sadok et al. [55], Wang et al. [67], EAF [18], Talukder [58]

1.2 Strengths and Weaknesses of MCDA

Belton and Stewart [4] presented the strengths and weaknesses of various MCDA techniques. MCDA leads to sensible, justifiable and explainable decisions. It helps to rank different options and find the most desirable outcome [16]. MCDA techniques are capable of considering a broad variety of conflicting but associated criteria [4, 70]. The strengths and weaknesses of MCDA from expert and stakeholder/participant perspectives are presented in Table 3.

1.3 Classification of MCDA Techniques

MCDA techniques come from various “axiomatic groups” and “schools of thought” (Herath and Prato [25]:5) and have been classified in a number of ways [8, 9, 17, 23, 25, 42]. According to Hajkowicz et al. [23], MCDA techniques are either continuous or discrete. Commonly, MCDA techniques are classified into (i) Multi-Objective Decision Making (MODM) and (ii) Multi-Attribute Decision Making (MADM). MODM deals with the decision problems in a continuous decision space, whereas MADM is suitable when all objectives of a decision problem need to be satisfied. In the literature, experts have classified MCDA techniques into many groups. Examples of the classification schemes of MCDA techniques by different experts are presented in Table 4.

1.4 Why Choose MCDA for Sustainability Assessment?

Sustainability assessment must integrate issues of economic, social and environmental interaction into decision making [14, 20, 58], and conflicting dimensions of economic, environmental, social, technical, human and physical issues are involved. Sustainability assessment aims to improve decision making in complex projects by involving the public and experts [19]. This is why MCDA is increasingly being applied to issues related to sustainability [25, 13, 58].

The assessment of sustainability is the key to ensuring sustainable development. For sustainability assessment of any development activities or any socioeconomic system, various information as well as stakeholders’ perspectives must be considered and integrated. Therefore, the assessment of sustainability can be considered a decision-making problem [55, 58] that requires a technique that is capable of integrating data from the three pillars of sustainability, following a transparent process, doing robust analysis and taking into consideration stakeholders’ opinions of sustainability criteria. MCDA techniques have this capacity as they follow a transparent

Table 3 Strengths and weaknesses of MCDA techniques

Strengths of MCDA techniques according to expert perspectives
• In the process of MCDA, the decision problems are broken down into segments of alternatives, criteria, weights and preferences.[1,2,4]
• MCDA helps to communicate the reasons for decisions in a logical and structured way[1]
• MCDA follows a transparent structural deliberation procedure.[1]
• MCDA can combine facts and social values.[1,6]
• Stakeholders can be involved in the decision making by assigning relative values to the criteria.[1,6]
• Stakeholders can take into consideration individuals' preferences about weights for the criteria.[1,3,6]
Weaknesses of MCDA techniques according to expert perspectives
• For many criteria, quantitative information is difficult to get.[1,2]
• It may be difficult to develop a scale for assessment purposes.[1]
• It is not clear whether the trade-offs of the criteria are considered in mathematical procedures.[1]
• It is assumed that preferences for the criteria are not dependent on each other.[1]
• There may be double counting in case of redundant or non-exhaustive criteria.[1]
• MCDA analysts cannot take part as decision makers as the may make biased decisions.[1,2]
• Resource constraints often restrain stakeholders' involvement in the MCDA procedures.[1,2]
Strengths of MCDA techniques according to stakeholder/participant perspectives
• MCDA allows the stakeholders to understand different points of view in decision making.[1, 2,3,5,6]
• MCDA helps the decision group and stakeholders to learn and move forward.[1,2,6]
• Stakeholders can concentrate on preferences and weights of the criteria rather than the final result.[1,2,6]
• MCDA considers both collective and individual voices for a decision.[1]
Weaknesses of MCDA techniques according to stakeholder/participant perspectives
• Complex procedures of MCDA may cause problems or difficulties because stakeholders may not understand them.[1,2]
• Analysts may focus on things that are not of interest to the stakeholders.[1]
• Stakeholders may not understand the technicalities of MCDA.[1]
• Experts may miss important criteria that are known by the stakeholders.[1]

Source Based on [1]Batstone et al. [2]:7–9, [2]Diakoulaki and Grafakos [15]; [3]Omann [48]; [4]Hobbs and Horn [29]; [5]Lahdelma et al. [36]; [6]Linkov et al. [38], Talukder [58]

structural process, are able to break down complex decision problems, can trigger discussion among stakeholders, can incorporate stakeholders' opinions on criteria and their weight and present the result visually [2, 39, 40, 58, 62, 69]. Therefore, MCDA techniques are applicable for sustainability assessment.

Table 4 Classification schemes of MCDA techniques

Polatidis et al. [50] classified MCDA techniques into three groups: (i) Outranking group. This group includes (a) Elimination Et Choix Traduisant la Realité (ELECTRE[1]) family (b) Preference Ranking Organization Method for Enrichment Evaluations (PROMETHEE[2]) I and II methods (c) Regime Method Analysis[3]
(ii) Value or utility function-based group. This group includes (a) Multi-Attribute Utility Theory (MAUT[4]) (b) Simple Multi-Attribute Rated Technique (SMART[5]) (c) Analytical Hierarchy Process (AHP[6]) (d) Simple Additive Weighting (SAW[7])
(iii) Other. This group includes (a) Novel Approach to Imprecise Assessment and Decision Environment (NAIADE[8]) (b) Flag Model[9] (c) Stochastic Multi-objective Acceptability Analysis (SMAA[10])
Hajkowicz and Collins [22] classified MCDA techniques into six groups (i) Multi-criteria value functions such as MAUT (ii) Outranking approaches such as PROMETHEE and ELECTRE (iii) Distance to ideal point methods such as Compromise Programming (CP[11]) and TOPSIS[12] (iv) Pairwise comparisons such as AHP (v) Fuzzy set analysis[13] (vi) Tailored methods[14]
Browne et al. [8] classified MCDA techniques into three groups (i) General utility analysis such as AHP (ii) Outranking methodologies such as PROMETHEE and ELECTRE (iii) Social multi-criteria evaluation (SMCE) such as NAIADE

[1] For details, see Roy and Vincke [52], Vincke [65]
[2] For details, see Brans and Vincke [6]
[3] For details, see Nijkamp et al. [47]
[4] For details, see Keeney and Raiffa [31]
[5] For details, see von Winterfeldt and Edwards [68]
[6] For details, see Saaty [54, 53]
[7] For details, see Polatidis et al. [50]
[8] For details, see Munda [43]
[9] For details, see Nijkamp and Vreeker [46]
[10] For details, see Lahdelma et al. [35]
[11] For details, see Abrishamchi et al. [1]
[12] For details, see Lai et al. [37]
[13] For details, see Hajkowicz and Collins [22]
[14] For details, see [56]

1.5 *Selection of MCDA Techniques for Sustainability Assessment*

All MCDA techniques come with pros and cons in terms of their ability to handle diverse information and weighting of the criteria. Specific techniques are suitable for specific situations [58]. For example, MAUT has the advantage of obtaining robust results and PROMETHEE has the advantage in ranking [11, 58]. Here, examples are presented of using MAUT and PROMETHEE to assess agricultural sustainability in light of these methods' capacity. These two methods were selected on the basis of prerequisites (see Table 5) of the nature and scope of the study, available information, selected criteria and stakeholder opinion. Brief descriptions of MAUT and PROMETHEE are given below in Sects. 6.1 and 6.2.

Table 5 Prerequisites of MCDA techniques for sustainability assessment

Prerequisites of MCDA techniques	Justification
Weights elicitation	Provide preference information among the sustainability criteria.
Critical threshold values	Operationalize the assimilative capacity of sustainability in terms of environmental, economic and social aspects
Comparability	Perform an integrated comparison among the agricultural systems
Qualitative and quantitative information	Handle the mixed information usually associated with agricultural sustainability assessment
Rigidity	Give robust results
Stakeholder involvement	Include a diverse audience of stakeholders
Graphical representation	Render the outcome understandable
Ease of use	Familiarize the stakeholders and assessors with the assessment process
Sensitivity analysis	Enhance the transparency of the procedure
Variety of alternatives	Incorporate all possible courses of action
Large number of evaluation criteria	Embrace all aspects of agricultural sustainability
Consensus seeking procedures	Reach a global compromise
Incorporation of intangible aspects	Consider "hidden" dimensions of the assessment
Incommensurability	Keep the decision criteria in their original units and provide a better composition of the issue
Treatment of uncertainty	Explicitly treat imperfect data (uncertain, imprecise, missing, erroneous, etc.)
Partial compensation	Operationalize a strong concept of sustainability
Hierarchy of scale	Decrease ambiguities and provide for explicit consistency
Concrete meaning for parameters used	Improve the reliability of the process
Learning dimension	Acknowledge and accept new information revealed during the evolution of the procedure
Temporal aspects	Consider the urgency of the situation and clarify long- and short-term concerns

Source Adapted and modified from [50] with permission

1.6 Multi-attribute Utility Theory (MAUT)

MAUT is widely applied in multi-criteria-based assessment [11] and is an important theory behind the procedure of MCDA [44]. In MAUT, the criteria can be assessed by integrating criterion values and relative or trade-off weighting [11]. A normalization process is applied to bring the criteria into a common dimension that is without unit [51, 58]. All the values of all the alternative criteria are combined and a single value score is generated, which enables comparison of the multiple preferences [12, 58]. Attributes of all criteria are used to evaluate the criteria. The relative importance of each attribute is reflected by weighting [45, 58]. MAUT can be applied to assess sustainability using the following formula:

$$v(x) = \sum_{i=1}^{n} w_i v_i(x)$$

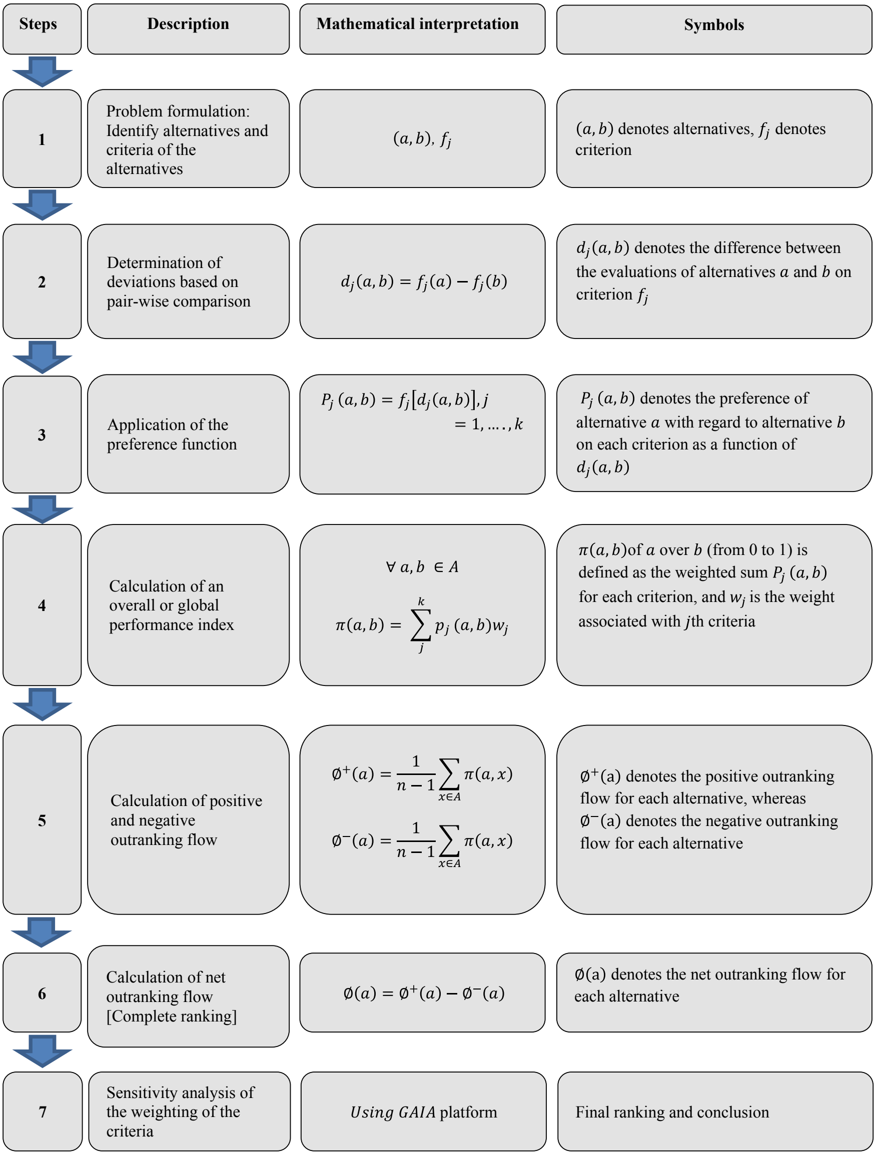
where

$v(x)$	is equivalent to the overall value of an alternative
n	is equivalent to the number of criteria,
w_i	is equivalent to the weight of criteria i, and
$v_i(x)$	is equivalent to the rating of an alternative x with respect to a criteria i.

Here, the $v_i(x)$ is normalized in a range of 0–1 and the relative importance (w_i) is given to the attribute i. Relative importance is assigned for each attribute/criterion by the values of worst to best [30]. MAUT structures the problem (value tree), making a reference model and finally conducting analyses [41].

1.7 Preference Ranking Organization Method for Enrichment Evaluations (PROMETHEE)

PROMETHEE, proposed by Brans et al. [5], is an outranking technique which is applicable for doing pair-wise comparison of the criteria to make a decision [66]. By considering quantitative and qualitative information of the criteria, it can generate a full ranking of the decisions from best to worst. This method is suitable where stakeholders' participation is required for decision making Hermans et al. [26, 33, 62]. Weighting of the criteria is an important aspect of PROMETHEE and depends on the decision makers' expertise. In this method, the preference function can be any of (i) strict, (ii) threshold, (iii) linear with threshold, (iv) linear over range and (v) stair step (level criterion). A narrative of these preference functions can be found in USACE and CDM [63]. The preference function values range from 0 to 1 [7]. The results of PROMETHEE can be visualised using Geometric Analysis for Interactive Aid (GAIA) software [4]. Figure 2 shows the steps for applying PROMETHEE to assess sustainability.



Steps	Description	Mathematical interpretation	Symbols
1	Problem formulation: Identify alternatives and criteria of the alternatives	(a,b), f_j	(a,b) denotes alternatives, f_j denotes criterion
2	Determination of deviations based on pair-wise comparison	$d_j(a,b) = f_j(a) - f_j(b)$	$d_j(a,b)$ denotes the difference between the evaluations of alternatives a and b on criterion f_j
3	Application of the preference function	$P_j\,(a,b) = f_j\left[d_j(a,b)\right], j = 1, \ldots ., k$	$P_j\,(a,b)$ denotes the preference of alternative a with regard to alternative b on each criterion as a function of $d_j(a,b)$
4	Calculation of an overall or global performance index	$\forall\; a,b\; \in A$ $\pi(a,b) = \sum_{j}^{k} p_j\,(a,b) w_j$	$\pi(a,b)$of a over b (from 0 to 1) is defined as the weighted sum $P_j\,(a,b)$ for each criterion, and w_j is the weight associated with jth criteria
5	Calculation of positive and negative outranking flow	$\emptyset^{+}(a) = \frac{1}{n-1}\sum_{x\in A}\pi(a,x)$ $\emptyset^{-}(a) = \frac{1}{n-1}\sum_{x\in A}\pi(a,x)$	$\emptyset^{+}$(a) denotes the positive outranking flow for each alternative, whereas $\emptyset^{-}$(a) denotes the negative outranking flow for each alternative
6	Calculation of net outranking flow [Complete ranking]	$\emptyset(a) = \emptyset^{+}(a) - \emptyset^{-}(a)$	$\emptyset$(a) denotes the net outranking flow for each alternative
7	Sensitivity analysis of the weighting of the criteria	*Using GAIA* platform	Final ranking and conclusion

Fig. 2 Steps in PROMETHEE analysis. *Source* Behzadian et al. [3], PROMETHEE 1.4 Manual [49], Talukder and Hipel [60] with permission

Table 6 Comparison of MAUT and PROMETHEE

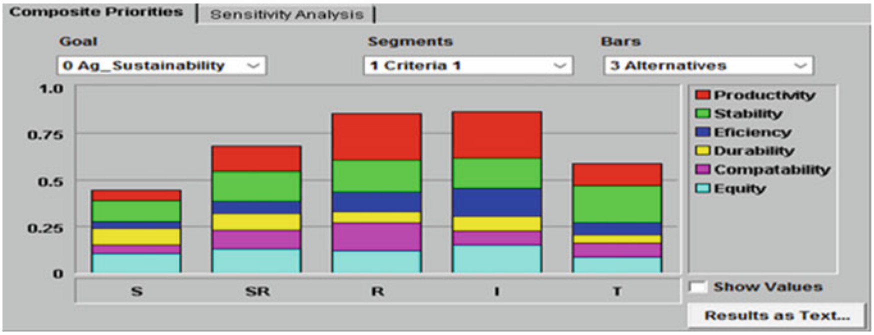
Comparison criteria	MAUT	PROMETHEE
Weighting	Many ways such as direct, swinging weights	When there are many criteria weighting is difficult, but for a small number of criteria weighting is possible
Threshold values	Determining threshold value for the criteria is not possible	Determining threshold value is possible
Compensability	Allow for full complete compensability of the criteria	Limited compensability
Capacity to handle quantitative and qualitative data	Can handle both quantitative and qualitative data	Can only handle qualitative data
Robustness	Preference ranks cannot be reversed	If the non-optimal alternative is considered, then rank reversals may take place
Decision making in a group	Allows group decision making as combination is relatively simple	Requires outside combination
Graphic Representation	Possible	Possible
User friendly	Simple to comprehend	Simple to comprehend
Sensitivity analysis	Possible	Possible
No. of alternatives	In theory no constraints	In theory no constraints
No. of assessment criteria	No limitation, but many criteria can be difficult to manage	Can support a large number of criteria
Incommensurability	Does not allow: all types of data must be normalized	Partially feasible
Uncertainty treatment	Possible	Possible
Hierarchy of scales	Possible	Not possible

Source Based on De Monti et al. [13], Mendoza and Martins [42], Polatidis et al. [50], Munda [44], Buchholz et al. [10], Cinelli et al. [11], Talukder [58]

Both MAUT and PROMETHEE offer advantages and disadvantages depending on the decision-making criteria. A comparison of both techniques is presented in Table 6.

1.8 Application of MAUT and PROMETHEE for Agricultural Sustainability Assessment

Examples of the application of MAUT and PROMETHEE for agricultural sustainability assessment are drawn from Talukder et al. [57] and Talukder and Hipel [60]. In both papers, the agricultural sustainability of five types of agricultural systems



Goal: 0 Ag_Sustainability

Segments: 1 Criteria 1

Bars: 3 Alternatives

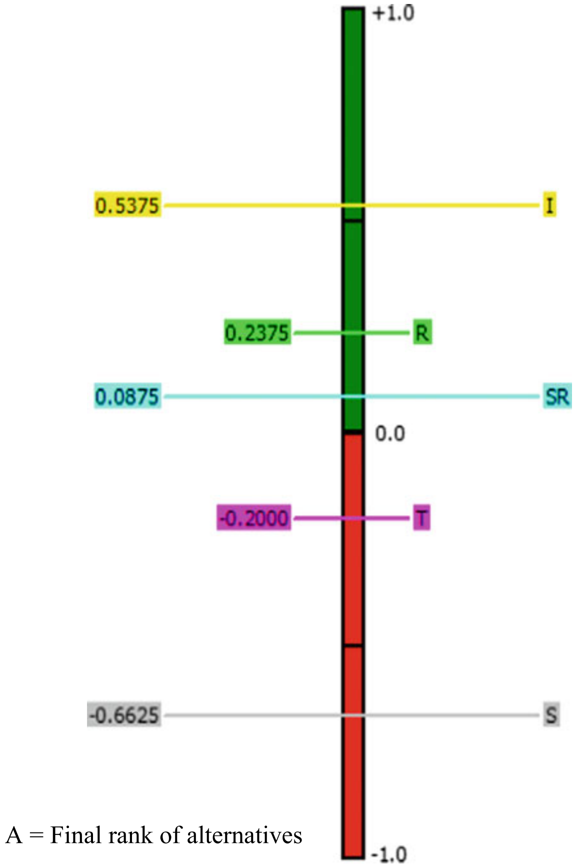
Fig. 3 Overall ranking of sustainability of agricultural systems using MAUT [57], with permission

is assessed: Bagda (shrimp)-based agricultural systems (S); Bagda-rice-based agricultural systems (SR); Rice-based agricultural systems (R); Galda (shrimp)-rice-vegetable-based integrated agricultural systems (I) and Traditional practices-based agricultural systems (T). Fifteen composite indicators (CI) drawn from six sustainability categories were used in the assessment: (i) Productivity (CI: Productivity); (ii) Stability (CI: Landscape stability, Soil health/stability, Water quality); (iii) Efficiency (CI: Monetary efficiency, Energy efficiency); (iv) Durability (CI: Resistance to pest stress, Resistance to economic stress, Resistance to climate change); (v) Compatibility (CI: Human compatibility, Biophysical compatibility); and (vi) Equity (CI: Education, Economic, Health, Gender). Overall assessment results of the two MCDA techniques are presented in Figs. 3 and 4.

A comparison of the merits and drawbacks associated with MAUT and PROMETHEE shows that both techniques are capable of assessing agricultural sustainability by considering a variety of data in different forms. Both techniques have the capacity to consider stakeholders' opinion and values in sustainability assessment to generate complementary information. The capacity to consider stakeholder opinion and weighting for criteria for sustainability assessment is an advantage of both techniques since most sustainability assessment techniques cannot take stakeholder perspectives into consideration [58].

Overall, both case studies feature MAUT and PROMETHEE as useful, systematic, analytical tools for sustainability assessment. The step-by-step methodologies proved to be useful and suitable for assessing and ranking sustainability. MAUT can break down complex problems, structure them in a transparent way, enable participation of the stakeholders and create a space for discussion, incorporate stakeholders' perspectives and present results visually and structurally [2, 39, 58]. Though it has some drawbacks, PROMETHEE's holistic approach makes it useful to assess and compare the aspects of sustainability [58].

Fig. 4 Overall ranking of sustainability of agricultural systems using PROMETHEE [60]



2 Conclusion

The cases in Sect. 6.1 demonstrate the applicability of MCDA techniques for sustainability assessment. More research is required to make the MCDA technique a commonly used approach to assess sustainability in different sectors. However, MCDA requires substantial mathematical knowledge for computation, which may make it less user-friendly. These challenges should motivate researchers to refine these techniques to assess sustainability.

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A Dynamic-Agent-Based Sustainability Assessment of Energy Systems

Mostafa Shaaban and Jürgen Scheffran

Abstract Energy plays an important role in our life, constituting one of the major vital needs of human beings and affecting all aspects of the development of our life. Until recently, electricity, the most widely used form of energy, represents an attractive field of research and development to many researchers in order to compromise between the efficiency and the economy of electricity supply technologies [2]. However, nowadays, climate change and its impacts direct the vision towards including other social and environmental aspects in the evaluation of these technologies [2]. In response to the increasing demand for electricity in Egypt, actors have to compare reasonably between all potential technologies and make decisions on the suitable energy-mix that could secure a sustainable future energy in Egypt. We introduce a new approach of a dynamic temporal and spatial sustainability assessment of technologies for electricity planning with the analysis of the decision-making process of multiple actors in the energy sector. Furthermore, we investigate the greenhouse gas (GHG) emissions from different energy-mix scenarios. Our results reveal an overall energy landscape transition towards renewable technologies in order to meet the increasing demand in a secure and sustainable manner with the possibility of including coal and nuclear energy to a limited extent as a diversification tool of energy resources ensuring more security. We conclude that the complexity of the decision-making process in the planning of future energy supply necessitates the involvement of a multi-dimensional dynamic assessment of energy systems and the involvement of preferences of all stakeholders, who are affected by the decision process, in the evaluation of these systems from their perspectives.

M. Shaaban (✉)
Leibniz Centre for Agricultural Landscape Research (ZALF), Eberswalder Str. 84, 15374 Müncheberg, Germany
e-mail: mostafa.shaaban@zalf.de

M. Shaaban · J. Scheffran
Research Group Climate Change and Security (CLISEC), Institute of Geography, Center for Earth System Research and Sustainability (CEN), University of Hamburg, Grindelberg 5/7, 20144 Hamburg, Germany
e-mail: juergen.scheffran@uni-hamburg.de

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Keywords Energy security · Sustainable energy · Egypt · Multi-criteria decision analysis · Agent-based modeling · Geographic information system

1 Introduction

1.1 Literature Review

With growing concern about the consequences of environmental change and their close relationship to energy development, the concept of sustainable development has been introduced, in addition to the need to involve key stakeholders, including end users, in the decision-making process [1]. Throughout the past three decades, there has been a major worldwide concern about sustainable development and the identification of indicators for sustainable energy assessment by many national and international organizations [2]. The International Atomic Energy Agency defines sustainable energy development as "The provision of adequate and reliable energy services at affordable costs, in a secure and environmental manner, and in conformity with social and economic development needs" [2, 3].

In 2011, ex-UN Secretary-General Ban Ki-moon launched the Sustainable Energy for All (SE4A) initiative and shared his vision for how governments, business and civil society, working in partnership, can make sustainable energy for all a reality by 2030 [2]. "Energy is the golden thread that connects economic growth, increased social equity, and an environment that allows the world to thrive", said Ban Ki-moon [2, 4]. The initiative is concerned with renewable energy resources as a key technology offering clean electricity, heating, and lighting solutions to people who mainly depend on conventional energy sources. Nevertheless, these technologies still face a range of social, economic and structural challenges, requiring not only further technological development but also a deeper understanding of both the success factors and the barriers to accomplish a widespread dissemination [2, 5]. In 2015, world leaders, at an historic UN Summit, have adopted 17 Sustainable Development Goals (SDGs) of the 2030 Agenda for sustainable development [2]. These goals came into force on January 1, 2016, aiming at accelerating efforts worldwide to end all forms of poverty, fight inequalities and tackle climate change, while ensuring that no one is left behind [2]. SDGs extend the success of the Millennium Development Goals (MDGs) and aim to go further to protect the planet [2]. The seventh goal of these SDGs is to ensure access to affordable, reliable, sustainable and modern energy fostering the objectives of the SE4A initiative [2, 6].

Energy security implies a concept of ensuring the availability of supply that could meet the demand. Some studies support the concept of separating the term security of supply from other policy objectives, e.g. economic efficiency and sustainability and to restrict the definition to the continuity of supply relative to demand [7]. However, in this study it is crucial to link the term security to sustainability. In a dynamic complex system, it is not wise to focus on a single assessment dimension of an alternative while performing applicability assessment of that alternative. A negative impact on other neglected dimensions would hinder the continuity of the provision of the resource. Therefore, we identify energy security as a provision of relatively efficient, harmless to human being as well as to the environment, affordable and socially acceptable energy supply that covers the basic demands of the community. We focus in this study on electricity security as one of the most vital forms of energy in this era.

During the period between 2010 and 2015, Egypt had experienced frequent electricity blackouts reaching its peak in 2014 because of rising demand, natural gas supply shortages, aging infrastructure, and inadequate generation and transmission capacity [2]. According to the United States energy information administration (US EIA), Egypt's generating capacity was 31.45 gigawatts (GW) in May 2015 which is slightly higher than the expected peak demand in 2015 of 30 GW [2]. Although the gap between the installed and peak capacity in 2018 has been increased reaching 55.2 and 30.8 GW, respectively, the fast increase in the installed capacity derives from the new installation of conventional power plants with a very slow progress in the renewable energy strategy. About 92.8% of the installed power in Egypt is supplied through combined cycle, gas and steam power plants which are all fueled by fossil-fuel, whereas 7.2% only is renewable energy of which 5.1% is hydro [8]. Recently, Egypt suffers from natural gas shortages, particularly during summer months [2]. As a result, it started to import fuel oil and diesel fuel to cover the shortfall [2, 9, 10]. So far, no previous studies of the sustainability assessment of electricity technologies in Egypt were investigated [2]. Based on interviews with energy experts in Egypt during February and April 2015, most of the electricity planning is pursued by assessing only the technical and economic aspects as evidenced by the study project "*Technical Assistance to support the reform of the Energy Sector*" (TARES) [2].

Going through the literature different methodologies have been applied to the evaluation of the complex energy system but from different perspectives. Liu [11], Singh et al. [12] and Ness et al. [13] provided an overview of various approaches to sustainability assessment including a composite index and a general sustainability indicator for renewable energy systems, as well as approaches to apply formulation strategies, scaling, normalization, weighing and aggregation methodology [2]. Pohekar and Ramachandran [14], Wang et al. [15] and Abu Taha [16] evaluated different multi-criteria decision-making (MCDM) models for sustainable energy planning and analysis [2]. Doukas et al. [17] assessed energy sustainability of rural communities using the principal component analysis (PCA) which is one of the MCDM models [2]. Troldborg et al. [18] developed and applied a multi-criteria analysis (MCA) to a national-scale sustainability assessment and ranking of 11 renewable energy technologies in Scotland and to critically investigate how the uncertainties in the applied input information influence the result [2]. Evans et al. [19] assessed the renewable electricity generation technologies against sustainability indicators [2]. Islam et al. [20] examined the current energy-mix, present energy crisis and its way to overcome such scenario by utilizing alternative energy sources such as biomass, solar, wind and small-scale hydropower energy, in the context of Bangladesh [2]. Góralczyk [21], Pehnt [22] and Varun et al. [23] investigated a dynamic approach towards the life cycle assessment (LCA) of renewable energy technologies [2]. Scheffran [24] discussed principles and criteria for establishing and evaluating a sustainable bioenergy lifecycle covering all dimensions of sustainability [2]. Demirtas [25] studied the best selection of renewable energy technology for sustainable energy planning using the analytical hierarchy process (AHP) methodology, another MDCM method [2]. There are many other studies that are concerned with the sustainability evaluation of energy systems for the future energy planning and decision-making process [2].

1.2 Conceptual Approach

In this chapter, we introduce a decision support system that would help decision makers to plan a rational future energy-mix scenario that could secure a sustainable electricity supply in Egypt till 2100 [2]. We investigate conditions, scenarios and strategies for future planning of energy in Egypt, with an emphasis on alternative energy pathways and a sustainable electricity supply mix as part of an energy roadmap till the year 2100 [2]. A novel approach is developed of integrating multi-criteria decision analysis (MCDA) with agent-based modeling (ABM) and geographic information system (GIS) visualization to integrate the time and site factors to assess the transformation of energy landscapes in Egypt [2]. Different electricity supply technologies are investigated and compared regarding multiple assessment criteria and multiple agents to achieve a comprehensive sustainability assessment covering technical, social, economic and environmental aspects of these technologies [2].

The research is guided by the underlying hypothesis that a holistic sustainability assessment underpins a transformation from the fossil-based energy system in Egypt towards alternative pathways developing the enormous renewable energy potentials of North Africa [2]. Starting from an understanding of the obstacles and lock-in effects of the current energy situation, the research aims at going beyond technical and economic fixes of established structures towards expanding the range of criteria and agents that reflect sustainable development in its multiple dimensions [2]. Scenario-based modeling and simulation represent shifting priorities of agents that shape the evolving energy landscape in Egypt [2].

We use the open-source ABM software "NetLogo 5.3.1" [26] to explicitly represent spatial agents across space and time as they decide on different energy pathways, taking into consideration environmental factors that vary across the landscape and create non-uniform environments for each energy type [2, 27]. We select seven principal technologies based on their potential resources in Egypt and the intention of the government to involve them in future planning [2, 27]. These technologies are coal-fired power plants, natural gas-fired power plants, wind, concentrated solar power (CSP), photovoltaics (PV), biomass and nuclear power plants [27]. Figure 1 shows a flowchart of our research process.

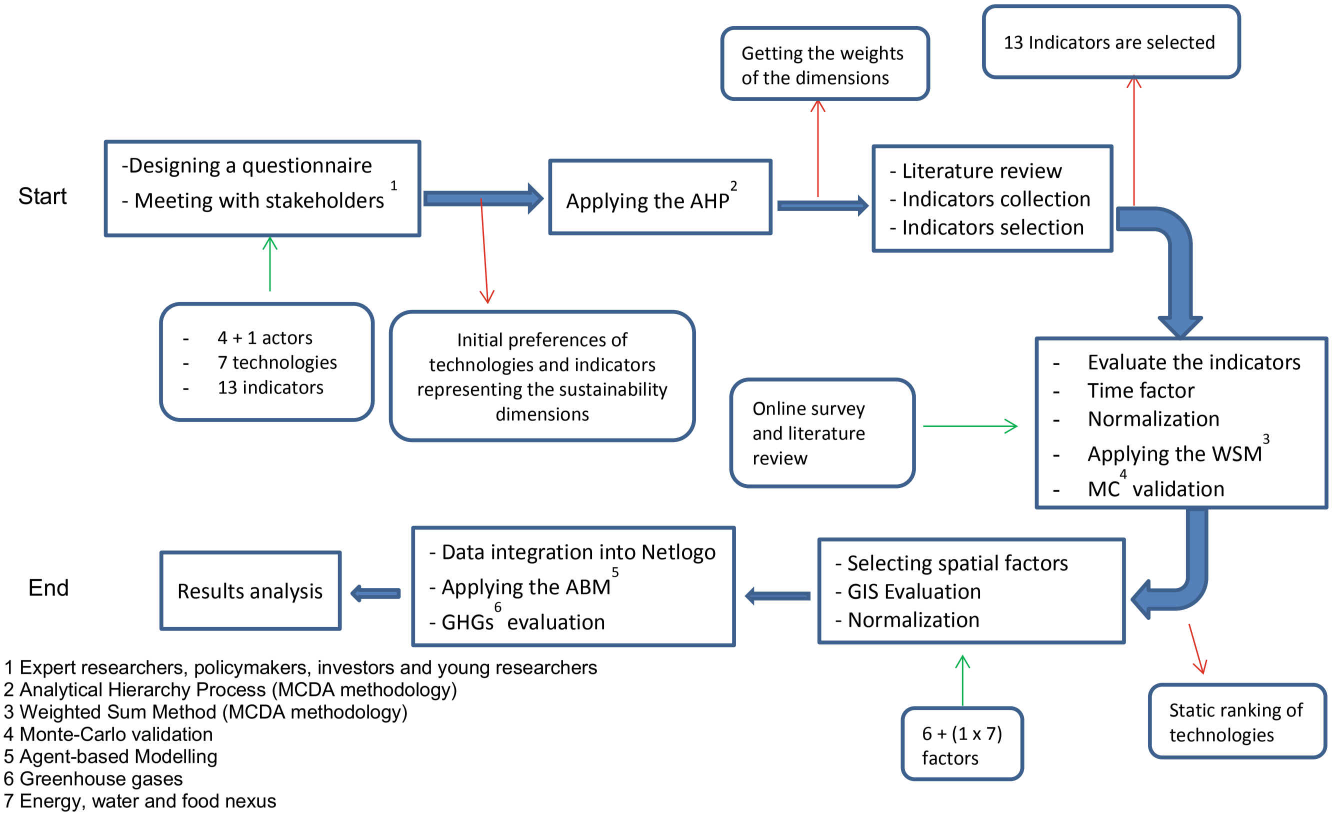


Fig. 1 Flowchart of the research process [2]

2 Materials and Methods

2.1 Empirical Data Collection and Analysis

Exploring previous studies, we found numerous energy indicators that have been used for the sustainable development assessment [1]. The United Nations Commission on Sustainable Development (UNCSD) derived 58 indicators from a working list of 134 indicators for applications worldwide [1, 12]. Neves and Leal [28] proposed a framework of 18 local energy sustainability indicators to be used both as an assessment and as an action-planning tool [1]. We collected a list of 72 indicators from a sample of 30 studies to be used as a pool of indicators from which we selected the most suitable ones for our case study [1]. According to a certain selection procedure [29], we selected 13 indicators as shown in Table 1 for the sustainability assessment of the technologies.

The values of the indicators have been collected through a literature review whereas their weights have been identified through a questionnaire that has been communicated to stakeholders in the energy sector through interviews with an objective to know the initial preference of different electricity supply technologies and the preference order of the sustainability assessment indicators in the evaluation of these technologies [1, 2, 27]. We targeted in our survey four groups of actors representing experts, policy-makers, investors, and young-researchers according to their affiliations [2]. Another virtual actor that we use in this study is based on the sustainable scenario where it represents equal initial preferences of all technologies and its progress while using equal weights of the sustainability dimensions [2].

Table 1 The selected assessment criteria (based on [2, 29])

Category	Indicator	Measuring Unit	Sustainability target
Economic	Investment cost	USD/kW	Minimize
	Job creation	Jobs/MW	Maximize
	Cost of electricity	USD/kWh	Minimize
	Operation and maintenance cost	USD/kW	Minimize
Environmental	CO_2 emission	g/KWh	Minimize
	NO_x emission	g/KWh	Minimize
	SO_2 emission	g/KWh	Minimize
Social	Safety risks	Fatalities/GW_eyr	Minimize
	Social acceptability	Ordinal scale	Maximize
Technical	Efficiency of energy generation	%	Maximize
	Resource Potential	TWh/year	Maximize
	Reliability of energy supply	%	Maximize
	Water consumption	kg/kWh	Minimize

Since the indicators have different measuring units, we apply the Min-Max normalization method as shown in the formulas in Eqs. (1) and (2) to get normalized values of the indicators while having the same relation of evaluation with regard to sustainability where some indicators are directly proportional to sustainability while others are inversely proportional to sustainability [1]. v is the value of the indicator, $v_{\max}$ and $v_{\min}$ are the maximum and minimum value of the indicator across the technologies, respectively. In order to avoid zero values of the indicator, the formula has been modified through reducing $v_{\max}$ by 10% in the first formula and increasing $v_{\max}$ by 10% in the second formula. Figure 2 displays a spider diagram of the normalized values of the assessment indicators per technology.

$$\frac{(v-(0.9 \times v_{\min}))}{(v_{\max}-(0.9 \times v_{\min}))} \tag{1}$$

$$\frac{((1.1 \times v_{\max})-v)}{((1.1 \times v_{\max})-v_{\min})} \tag{2}$$

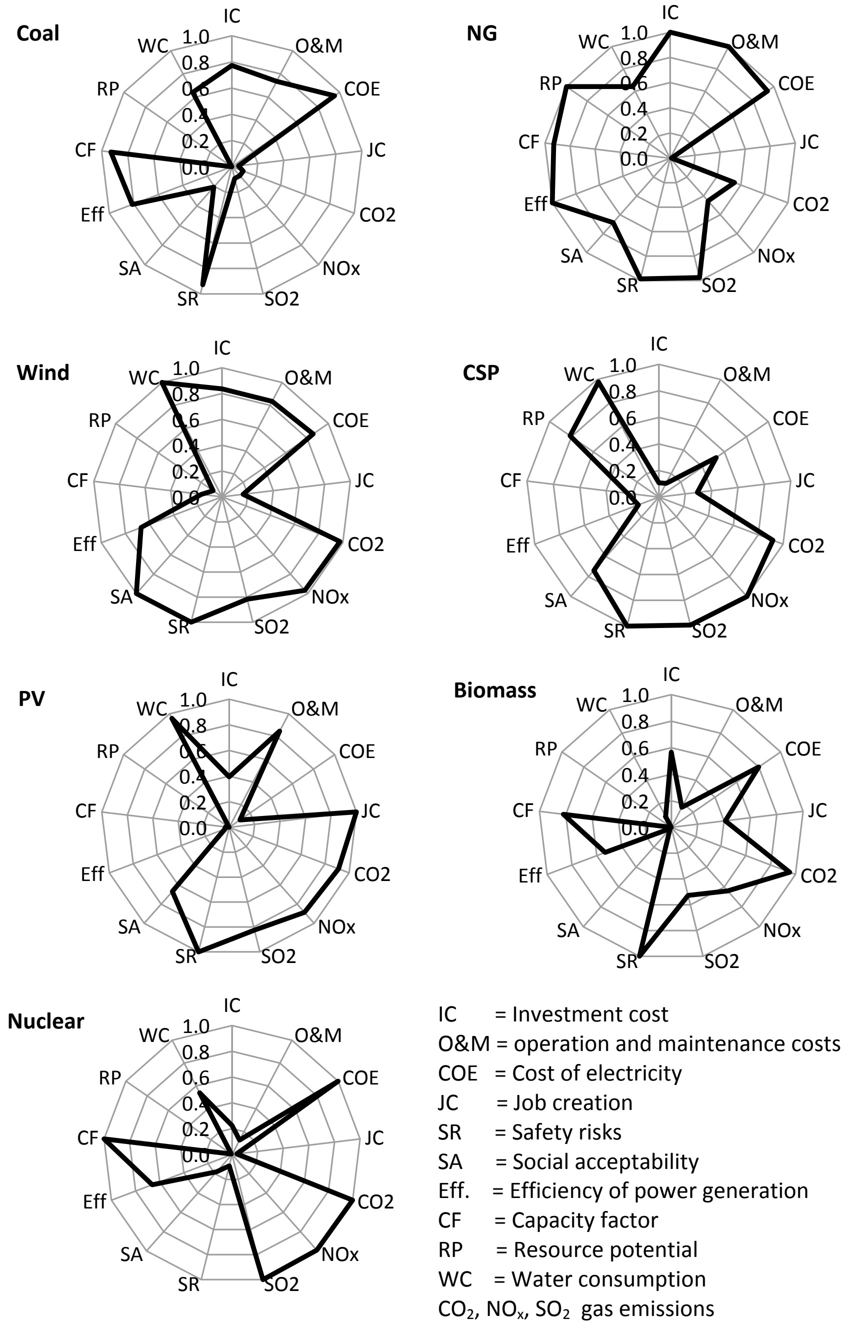
2.2 The Multi-criteria Decision Analysis

The multi-criteria decision analysis MCDA is based on comparing different alternatives through identifying a set of evaluation criteria that are applicable to all of these alternatives [27]. The values of these criteria are then normalized, and their weights are determined according to the relative importance of the criteria [27]. The main objective of MCDA is to integrate the weights and the normalized values of the criteria so that each alternative is associated with an integrated value that reflects its ranking [15, 27]. It plays an important role in energy systems planning, especially after the concern on environmental protection has increased [2]. We apply two MCDA approaches in the sustainability assessment of the technologies, the analytical hierarchy process (AHP) and the weighted sum method (WSM) [27].

The analytical hierarchy process (AHP) is based on the decomposition of a complex problem into a hierarchy with an objective at the top of the hierarchy, indicators and sub-indicators at levels and sub-levels of the hierarchy, and decision alternatives at the bottom of the hierarchy as shown in Fig. 3 [1, 14]. We evaluate the weight of the indicators in a pair-wise comparison using the scoring system presented in Table 2, based on their importance regarding energy technology selection according to the perspectives of the stakeholders who have been interviewed [2].

The weighted sum method (WSM) is the most commonly used approach in sustainable energy systems [15] that satisfies the following expression [27]:

$$A_i = \sum_{j=1}^{n} \left(a_{ij} w_j\right), \ \text{for } i = 1, 2, 3, \ldots .m \tag{3}$$



IC = Investment cost
O&M = operation and maintenance costs
COE = Cost of electricity
JC = Job creation
SR = Safety risks
SA = Social acceptability
Eff. = Efficiency of power generation
CF = Capacity factor
RP = Resource potential
WC = Water consumption
CO_2, NO_x, SO_2 gas emissions

Fig. 2 Normalized multi-criteria evaluation of energy systems [1]

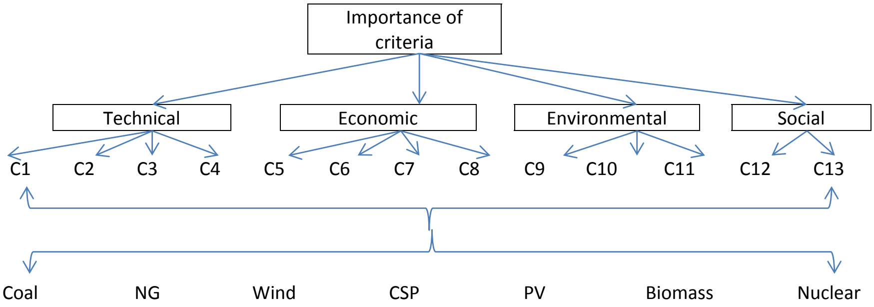


Fig. 3 AHP framework for assessing the weights of the indicators [1]

Table 2 Scoring scale of AHP and its interpretation [15, 27]

Scale	Degree of preference	Scale	Degree of preference
1	Equal importance	7	Very strong
3	Weak	9	Extreme importance
5	Strong	2, 4, 6, 8	Intermediate values

where A_i is the WSM score of alternative i, n is the number of decision indicators, m is the number of alternatives, a_{ij} is the normalized value of the jth indicator in terms of the ith alternative and w_j is the weight of the jth indicator that has been obtained from the AHP [27]. The total value of each alternative is equal to the sum of products, which is ultimately used to rank, screen or choose an alternative with the maximum score [27]. From this step, we can get the ranking of the technologies which corresponds to the general integrated sustainability index as calculated through the WSM [27].

2.3 GIS-Based Spatial Data Analysis

With this tool, we evaluate the influence of some important spatial factors that represent the local conditions on the selection of an energy pathway [2]. We selected seven spatial factors: resource potential, population density, primary roads availability, water availability, grid availability, political stability and the negative impact potential on crops [2]. We build these data sets as layers of raster data and rank the locations using the WSM. Figure 4 depicts an example of the spatial ranking of the resource potential of wind energy based on a wind atlas map.

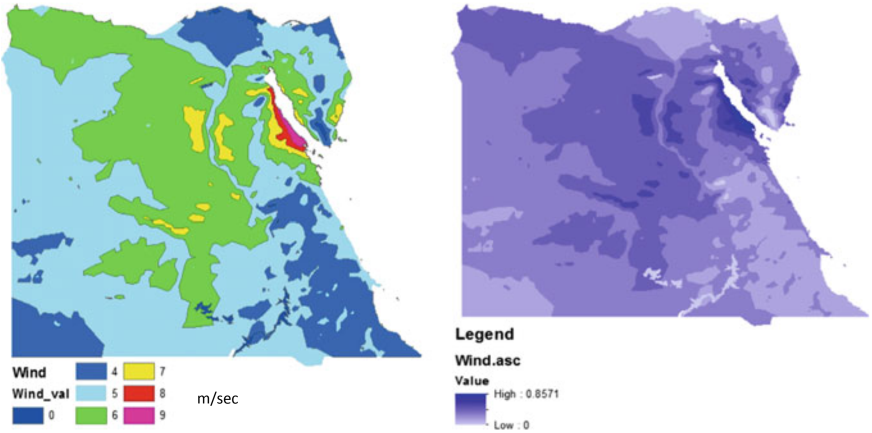


Fig. 4 Spatial ranking of wind resource potential in Egypt [2] (The left map is based on [30])

2.4 Agent-Based Modeling (ABM)

Agent-based models reflect the temporal dynamics of the decision-making process based on cost–benefit analysis [2]. In comparison with variable-based approaches using structural equations, or system-based approaches using differential equations, agent-based simulation is a bottom-up modeling approach which offers the possibility of modeling individual heterogeneity, representing explicit agent decision rules, and situating agents in a geographical or another type of space [27, 31, 32]. An agent-based model consists of a set of agents, their relationships, rules of behavior and a framework for simulating agent behaviors and interactions [2]. Here, the ABM is built on agents who act by adjusting their priorities (*p*) for action pathways (*A*) in response to the change in the marginal values of the pathways as a function of costs (*C*) and value preferences (*V*) as well as environmental conditions (*E*) that change in space and time as shown in Fig. 5 for a description of the VCX model

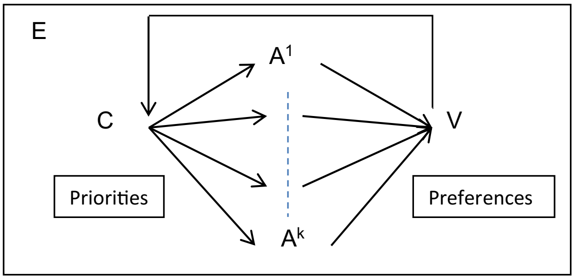


Fig. 5 An illustrative diagram of the VIABLE agent-based model (based on Scheffran and Hannon [33]). It describes the allocation of priorities (*p*) of investment (*C*) to action pathways (*A*) affecting value preferences (*V*) under changing environmental conditions (*E*) [27]

framework see [2, 33]. We modified and expanded this ABM approach by including value functions based on the MCDA assessment models as well as expert evaluations and the projected future electricity demand to compare different energy pathways used in electricity-mix scenarios and sustainability of land use [27].

The multi-criteria analysis is applied to classify typical agents characterized by weighted priorities for certain criteria sets [2]. These types of agents are then used in agent-based models where agents follow these priorities to select energy pathways that meet these criteria [2]. Agent decision rules are applied to a GIS-based spatial (cellular) model landscape, taking into account spatially specific environmental and socio-economic conditions [2].

The dynamics of changing action priorities for energy pathways describes agents that iteratively shift their action pathways towards large marginal value-cost preferences by comparing the marginal value of one pathway with the weighted average marginal value including all pathways [2]. This is given by the following evolutionary equations [2] of shifting priorities for action pathway k of actor type q in spatial cell (agent) i:

$$\frac{\Delta p_{\mathrm{iq}}^{k}}{\Delta t} = \alpha_{\mathrm{iq}} p_{\mathrm{iq}}^{k} \left(v_{\mathrm{iq}}^{k} - \sum_{l} p_{\mathrm{iq}}^{l} v_{\mathrm{iq}}^{l} \right) \tag{4}$$

- $\frac{\Delta p_{\mathrm{iq}}^{k}}{\Delta t}$ is the change in action priority p of actor q for energy pathway k in spatial cell i for time period Δt which is one year in our case.
- α_{iq} is the adaptation rate of actor q in spatial cell i (in this study we apply the same adaptation rate for all actors).
- $\sum\limits_{l} p_{\mathrm{iq}}^{l} v_{\mathrm{iq}}^{l}$ is the sum of weighted marginal values (average) including all energy pathways l.
- v_{iq}^{k} is the marginal value of energy pathway k for actor q in spatial cell i which is a function of the value and the weight of the spatial factors and the assessment indicators:

$$v_{\mathrm{iq}}^{k} = \frac{\left(\frac{\left(\sum_{m=1}^{o} s_{\mathrm{mi}}^{k} \times h_m\right)}{\sum_{i=1}^{z}\left(\sum_{m=1}^{o} s_{\mathrm{mi}}^{k} \times h_m\right)} \right) \times \left(\sum_{j=1}^{n} a(t)_{kj} \times w_{\mathrm{jq}} \right)}{\sum_{k=1}^{l} \left[\left(\frac{\left(\sum_{m=1}^{o} s_{\mathrm{mi}}^{k} \times h_m\right)}{\sum_{i=1}^{z}\left(\sum_{m=1}^{o} s_{\mathrm{mi}}^{k} \times h_m\right)} \right) \times \left(\sum_{j=1}^{n} a(t)_{kj} \times w_{\mathrm{jq}} \right) \right]} \tag{5}$$

- s_{mi}^{k} is the value of spatial factor m influencing spatial cell i which is for some factors specific to energy pathway k as in case of the resource potential, where z is the number of spatial agents
- h_m is the weight of the spatial factor m, where o is the number of spatial factors.
- $a(t)_{\mathrm{kj}}$ is the value of the assessment indicator j for energy pathway k which is for some indicators a function of time.
- w_{jq} is the weight of the assessment indicator j of actor q, where n is the number of the assessment indicators.

In this chapter, we are concerned with the analysis of the decision of four categories of actors who represent energy planners selecting among energy system technologies that could supply the growing electricity demands although actors from other sectors could influence and be affected in this system [2]. In one of the investigated scenarios which we call the game scenario, the four types of actors (experts, policy-makers, investors, and young-researchers) together with the sustainable scenario interact with each other where the decision by one actor would influence either positively or negatively another actor [27]. The other actors could thereafter improve the values of the indicators of the technology they prefer and/or reduce the values of the technologies they do not want in the future. For instance, actors who have interest towards renewable energy would support the development of this type of technology by raising the awareness of the public towards the hazards of fossil-fired and nuclear power plants and the environmental advantages of renewable energy technologies so that they can increase the social acceptance in the future.

In the game scenario, each actor has set up an initial preference of the sustainability dimensions and an initial preference of the technologies [2]. The target of the game is to achieve the maximum value of the maximum priority technology in each spatial cell relative to the other actors. Here the actors compare their results in each step in the game scenario with their own individual evaluation. They can observe how much deviation exists from their plan. There is a feature in the model which displays the actor with highest priority technology in each cell. The logic of the game scenario came from the individual ranking of the technologies based on the MCDA in each cell. However, the highest rank technology could have a value that differs from one actor to another. These rankings are based on the weights and the values of the indicators and the spatial factors as well. We do not evaluate the impact of the ranking on the values of the indicators but rather on the preferences of the indicators which is derived from the decision behavior of the actors. The rational distribution of the preferences of the assessment indicators would end up with the highest rank technology. Thus, we encourage the actors by this game scenario to change their decision behavior in the preference of the assessment indicators. For the future, other game scenarios are possible based on collective decision-making representing a majority or joint benefit decision rule [27].

Figure 6 shows a schematic diagram of the potential interaction between several direct and indirect actors in the future planning of electricity supply. Further details about the model can be found in [34]. Figure 7 depicts our programmed model interface in NetLogo.

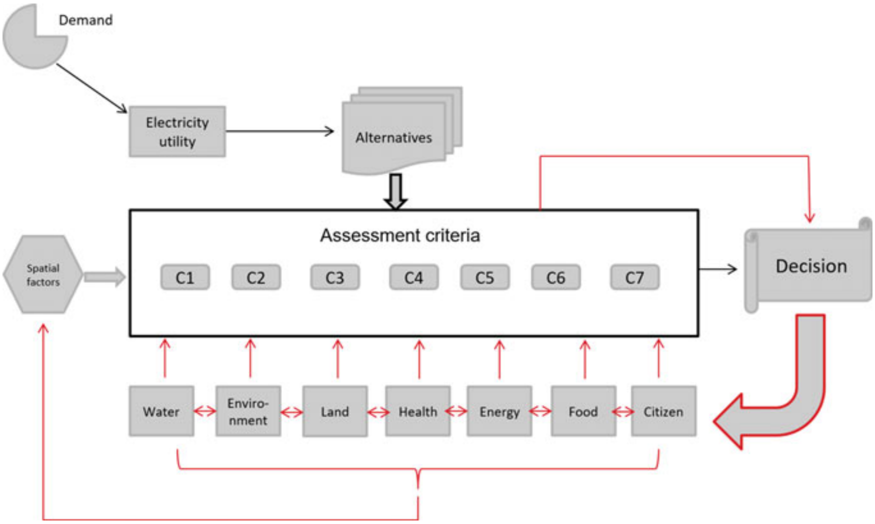


Fig. 6 A schematic diagram describing the principle of the integrated assessment

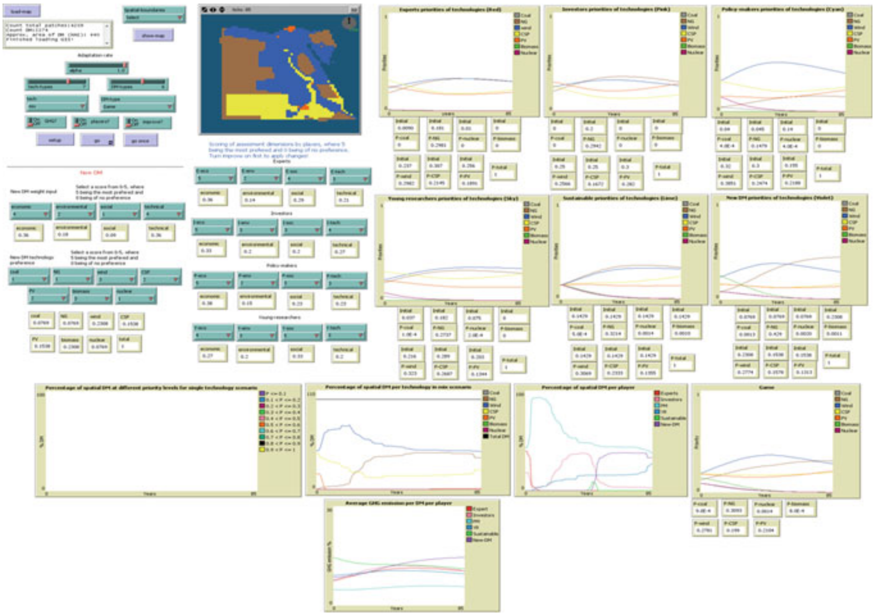


Fig. 7 Model interface in NetLogo [2]

3 Results and Discussion

3.1 *Energy Landscapes Transition*

Figure 8 compares the adaptive changes of priorities of the technologies aggregated over all spatial cells between the four actors (Experts, Investors, Policy-makers and Young-researchers), the sustainable scenario and the game scenario for each type of

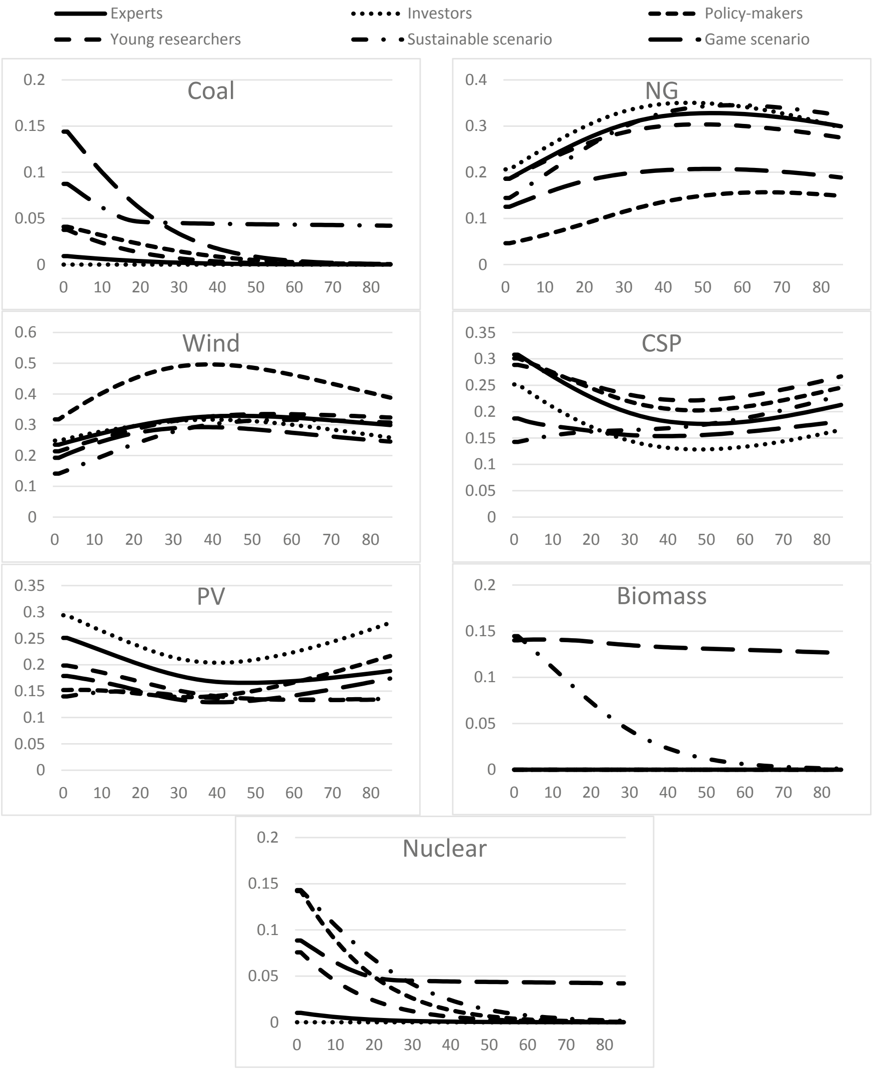


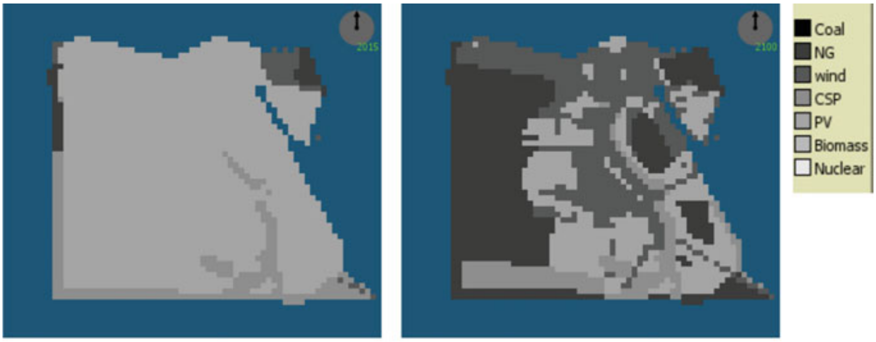
Fig. 8 The average priorities of the technologies per actor type changing with time

technology throughout the years 2015–2100 (i.e. 0–85 time steps in NetLogo) [27]. In the scenario of "Experts", it can be observed that the model starts with the highest average priority to CSP followed by PV, wind and NG. Nuclear and coal are almost of zero priority throughout the running period of the model for both experts and investors, however, they started in the policy-makers and young-researchers scenario at a very low level above zero but again they step down drastically approaching zero. In general, there is a gradual increase in the priorities of both wind and NG which starts to decrease again after approximately 40 years with an opposite pattern to both CSP and PV. This implies that the potential tendency towards both CSP and PV will start after 2050 giving less attention to wind and NG by these actors. However, this changing pattern exists at different levels between actors. In the scenario of "Policy-makers", the priority of wind is higher than that of other actors showing more affinity towards this technology. This supports the tendency of the government to increase the investments in wind energy projects where the installed power from wind has been increased from 547 MW in 2015 to 967 MW in 2018. Additionally, about 4610 MW wind power plants are planned to be installed by 2023 [8]. This scenario also shows a lower priority curve of NG than that of CSP and PV. In the sustainable scenario, the priorities of wind and NG are almost coinciding whereas for CSP and PV, they bifurcate starting from the middle of the model running period showing an increasing trend to CSP and a decreasing trend to PV but at a lower rate than that of CSP [2].

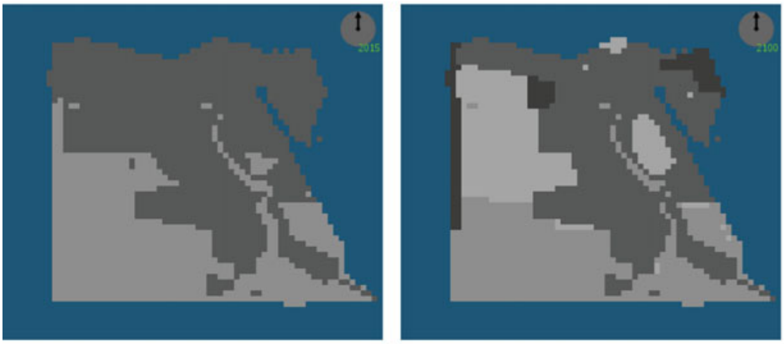
The map visualizations of the energy landscapes for three scenarios at year 2015 and 2100 are presented in Fig. 9. They elucidate the spatial DMs (cells) with the maximum priority technology for three different actors changing with time. In the "Investors" scenario, the landscape starts with about 85% coverage with PV while having the rest being distributed between CSP, wind and NG. However, this enormous coverage comes to zero after about 20 years, whereas the coverage of NG and wind increases simultaneously covering 50% and 44% of the cells, respectively. Later on, the technology coverage starts to change again where NG decreases to the wind coverage level, then both decrease together until NG covers 36% of the cells and wind covers 26% of the cells. At the same time CSP and PV start to increase gradually, where the former reaches at the end of the model run 10% while the latter reaches 26% coverage [2].

In the "policy-maker" scenario, the landscape starts with close percentage coverage between CSP (40%) and wind (60%). The coverage of wind increases at a slow rate with time while it decreases for CSP until after 35 years they behave in opposite way but with keeping the wind at a higher coverage percentage than CSP till 2100 [2].

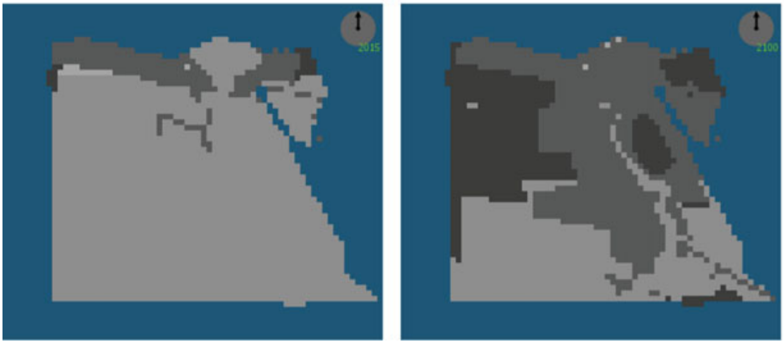
In the "Young-researchers" scenario, the landscape starts with CSP coverage of about 85% and 10% coverage of wind with the remaining 5% distributed between NG and PV. While the CSP coverage decreases as the model runs, the wind and NG coverage increases until reaching an equilibrium with a predominating wind coverage of 43%, NG coverage of 33% and CSP coverage of 23% after 25 years. This equilibrium lasts with this approximate coverage distribution till 2090 where the priority of CSP exceeds over that of NG in about 7% of the cells [2].



a: Investors 2015 b: Investors 2100



c: Policy-makers 2015 d: Policy-makers 2100



e: Young researchers 2015 f: Young researchers 2100

Fig. 9 Energy landscape transition displaying the maximum priority technology per scenario in 2015 and 2100 [2]

3.2 Future Projected Energy-Mix

The following part presents the predicted electricity-mix scenarios based on the preferences made by the actors and the dynamic assessment of the technologies. Based on the average priorities of the technologies that are presented in Fig. 8, we

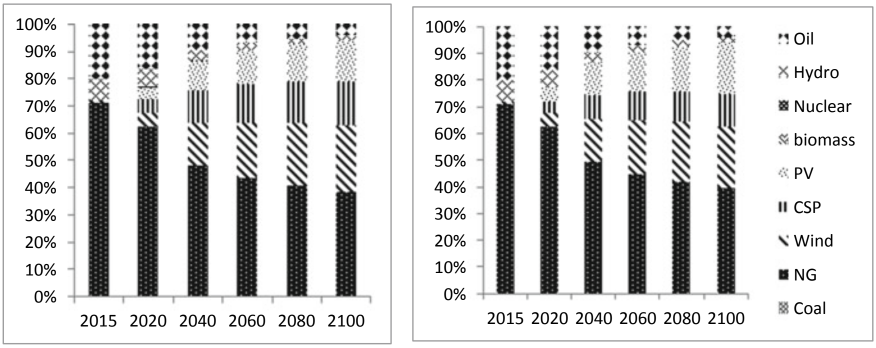
Table 3 Electricity-mix data of Egypt in 2014 [10]

	Hydro	NG	Oil	Wind	Solar
TWh	13.4	119.3	34	1.3	0.02
% TWh	7.9	70.9	20.3	0.8	0.01

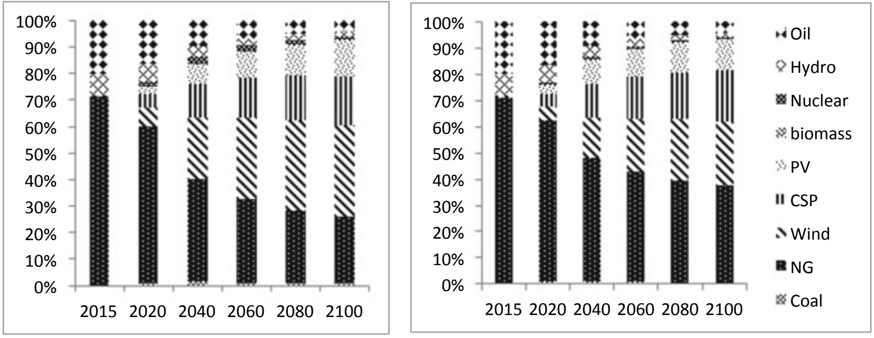
calculate the future projected energy-mix. In 2015, we use the actual energy-mix in Egypt at year 2014 based on the energy produced not on the installed capacity which are shown in Table 3. We use the predicted future electricity consumption and calculate the amount of the predicted electricity demand during each period. The priority-mix of the technologies for each actor is multiplied by the amount of the predicted electricity demand giving a new energy-mix distribution. For instance, if 30 TWh (Terawatt hours) of electricity will be needed to be supplied between 2015 and 2020, therefore the priorities will be distributed on this amount, and then it will be added to the previously existing amount. We assume that the old systems will be included in the energy-mix and not be substituted nor decommissioned [27].

The values of the energy-mix in percentage are shown Fig. 10. It has been found that coal in 2020 ranges between completely absent in the energy-mix as preferred by investors to about 2% in the sustainable scenario which corresponds to 0.8 GW but 0.5 GW would be accepted by all actors according to the game scenario (cf. [8] which states that the 4640 MW coal power plant in Oyoun Moussa is planned to operate by 2027 and 6600 MW in Hamrawein). In 2100 coal would be accepted not to exceed 4% of the energy-mix with an installed capacity in the range of 5 GW. The share of NG which constitutes about 70% of the energy-mix in 2015 is expected to be reduced to about 60% with an installed capacity of about 23 GW in 2020. There is no big difference in the prediction levels of NG between actors in 2020, however, in 2100, the gap increases between actors regarding this technology where it ranges between 25 and 40% share in the energy-mix which corresponds to a predicted installed capacity ranging between 36 and 58 GW [2].

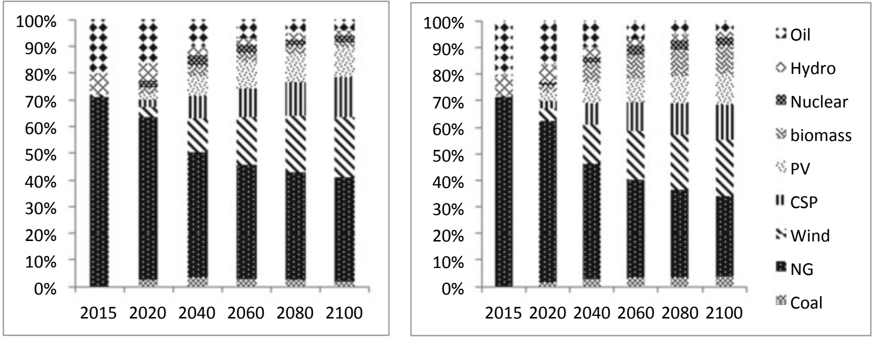
Wind share is predicted to have an average value of 5% with a range of 3.5–7% in 2020 of the generated energy and an installed capacity of about 5 GW. In 2100, there is also a big difference between actors' predictions where the share of wind ranges between 20 and 35%, which corresponds to an installed capacity range of 70–113 GW. For CSP, the share ranges between 2.7 and 5% with an installed capacity ranging between 5.5 and 10.5 GW in 2020 [2]. Whereas in 2100 the share of CSP will rise to a range of 12–20% with an average installed capacity of about 120 GW [2]. PV share is expected to have the same range like that of CSP in 2020 and 2100 in accordance to the preferences of different actors. Moreover, the installed capacity will be in the range of 3–6 GW in 2020 and 50–85 GW in 2100 which differs from that of CSP due to the differences in the full load hours [2]. It is recommended by the sustainable scenario to include a share of 2.2% of biomass in 2020 and 2100 as a diversification of technology security like in coal [27]. The same applies to nuclear technology where the share ranges from 0 to 2.2% in 2020 at an average installed capacity of 0.4 GW. Although the range of shares is preferred to be kept unchanged,



Experts Investors



Policy-makers Young-researchers



Sustainable scenario Game scenario

Fig. 10 Predicted energy-mix for Egypt in percentage according to actors' priorities

however, the installed capacity will be increased to an average value of 2 GW in 2100 [27].

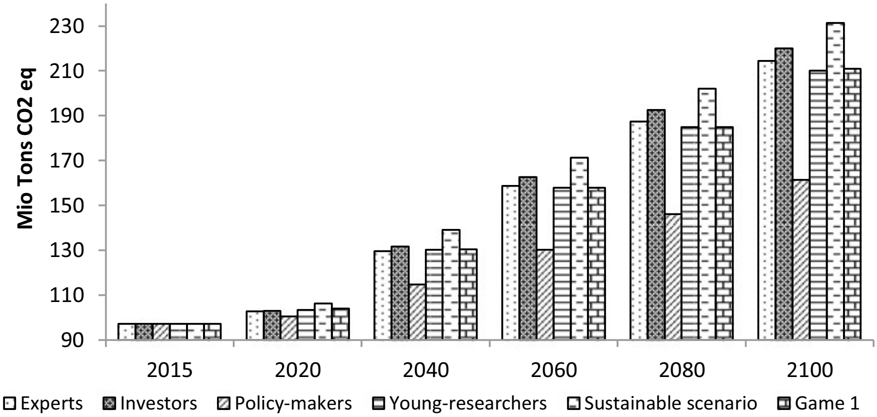


Fig. 11 A comparison of the GHG emissions of the energy-mix of the technologies

3.3 GHGs Assessment

An important output of the model represents a comparative investigation of the contribution to climate change and global warming from the different energy-mix scenarios as obtained from the analysis of the decisions made by actors in the assessment of the technologies [2]. Figure 11 illustrates the GHG emissions in million tons CO_2 equivalent (Mio tons CO_2 eq.) from the energy-mix estimated by each actor over the whole period. It has been found that the proposed energy-mix scenario by policymakers emits lower GHGs as compared to other scenarios while the sustainable scenario shows the highest probability of GHG emissions due to the inclusion of biomass and a higher value of coal [2]. However, the emission from the sustainable scenario approaches to that of the other three actors [2]. We can conclude from these graphs that the average GHG emissions would be doubled in 2100 which might contribute negatively to climate change [2].

4 Summary and Conclusion

According to the results shown in this chapter, we conclude that the decision-making process in the energy sector to secure future electricity supply for the coming generations is a complex process [2]. It involves a multi-dimensional analysis of all possible potential technologies through the evaluation of indicators whose values change in space and time and change also due to the impact of the interactive decision-making process of multiple actors [2]. Moreover, the actors involved in the decision-making process have different preferences for these indicators and their decisions could be affected by the decisions of other actors [2]. Although the sustainable scenario constitutes a normative decision approach with unbiased affinity towards any of the sustainability dimensions, making it a target for all countries in their energy planning, in practice, there are many actors who decide differently and interact with each other [2]. Therefore, a balanced energy-mix resulting from the interaction of the actors in the game scenario could represent a realistic and better approach of predicting an acceptable and sustainable future secure energy-mix in Egypt [2]. The results of the game scenario show how important it is for the Egyptian government to show more concern for renewable energy projects and the transition of the energy landscape from fossil-fuel-fired energy systems to renewable ones. Energy diversification, through the inclusion of other resources like coal or nuclear in a limited amount, adds more security through gaining knowledge and experience of their operation [2].

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Preparing for the Unpredicted: A Resiliency Approach in Energy System Assessment

Mohammad Zaher Serdar and Sami G. Al-Ghamdi

Abstract Looking at cities these days, we could observe the advanced level of developments and integration of technologies in all sectors and systems. However, at the same time, we are living in a changing world. In recent years, humans started to realize the cost of this development and the burden laid on the planet due to human activities. This increase in complexity, challenges, and uncertainties fueled the need to adopt a resiliency-based design approach. In this book chapter, we address the resiliency in energy systems definition, some assessment methods, and the integration of renewable energy sources on it. Also, we added two real case studies that further explain resiliency repercussions and enhancement practices. Nevertheless, considering the importance of mutual dependency and security of critical systems, we highlight these nexuses between energy and some of the critical systems within the scope of resiliency.

Keywords Resiliency Assessment · Energy systems · Renewable sources · Interdependency · Nexus

1 Introduction

Looking at cities these days, we could observe the advanced level of developments and integration of technologies in all sectors and systems. Cities today are far sophisticated than ever; they are very interconnected and supported by interdependent systems. These systems are essential to provide the expected services, life quality, and thriving population. Interconnected and integrated critical systems increase efficiency and manageability but introduce several problems. Interdependent and sophisticated systems reduce flexibility and expose the overall system of systems to cascading failure, where a problem in one system could propagate into others [1].

Energy systems are essential for the functionality of all other critical systems. Energy systems, whether electrical, fuel, or gas, play a vital role in keeping urban

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M. Z. Serdar · S. G. Al-Ghamdi (✉)
Division of Sustainable Development, College of Science and Engineering, Hamad Bin Khalifa University, Qatar Foundation, Doha, Qatar
e-mail: salghamdi@hbku.edu.qa

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systems running. For instance, Water pumping, treatment, and distribution are all energy-intense processes, let alone wastewater collecting and treatment. Moreover, fuel powers vehicles' mobility in the transportation system, while electricity allows the function of traffic control and management equipment. The role of the energy system extends to buildings for heating, cooling, processing food, and almost all activities in buildings [2].

However, at the same time, we are living in a changing world. In recent years, humans started to realize the cost of this development and the burden laid on the planet due to human activities. Anthropogenic effects, coupled with the natural cycle of the planet, started to induce climate change. Researchers started to observe it through many phenomena like unusual temperature extremes, precipitation patterns change, and unprecedented disasters. The extreme intensity of these stresses is not the only disturbing part, but the rate of these extreme events which unmatched with any previous records [1–3].

The impact of climate change on cities is severe and hard to address with the usual design method. Traditional design practices rely on previous records of extreme events to calculate design capacity. However, the increase in rates and intensities of climate-change-linked disasters has undermined the effectiveness of these practices. Moreover, the interdependency of critical systems means that the failure of one system will affect the performance of other critical systems. Furthermore, the concentration of economic value and human capital means any interruption of critical systems will have a high cost. Researches mimicked nature and adopted the concept of resiliency as an answer to this challenge [4–6].

Resiliency concept was first reported in 1973 by Holling [7], while he was describing the ecological system's ability to absorb and recover from disturbance. Later on, about two decades ago, the concept found its way to engineering disciplines and researches, so it is a relatively new concept in engineering [8]. Resiliency in engineering disciplines is generally regarded as a combination of properties that describe the way a system reacts with a disturbance and recovery from it. Most notable of these properties are "vulnerability, Robustness, Survivability, Reliability, Flexibility". Furthermore, these properties are to some level related to risk management [9]. However, the contribution of these properties varies from one assessment method to another based on different definitions of resiliency, as described in Fig. 1.

1.1 Resiliency Definitions

When dealing with resiliency, researchers have suggested varying definitions. This variation stems from several considerations like:

- The scope of the assessment. The assessment could range in scale from element level to whole-system evaluation.

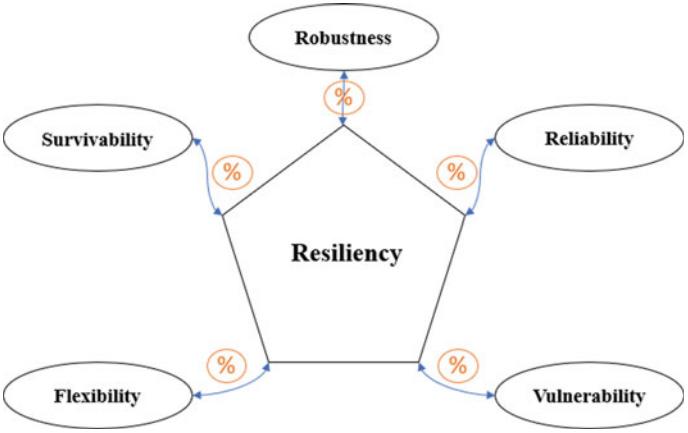

Fig. 1 Resiliency components

- The chosen indicator or metric. Indicators could vary widely from network discontinuity, supply shortage, or even reduction in service provided. This variation stems from resiliency definitions and assessment methods.
- The nature of the disturbance. Environment-induced disturbances have random impact points, while human-made events focus on valuable targets or elements in the system.
- The stage of interest. This especially sensitive for enhancement methods, whether it is impact reduction or recovery oriented.

However, most of the definitions converge at the system ability to absorb the impacts and the time needed to regain standard functionality. So, we can define resiliency as: "system ability, under a disturbance, to absorb the induced impact with minimum damage or interrupt in the service and return to its normal level of functionality within an acceptable timeframe."

This definition suits various interpretations and modifications for different systems and domains. Furthermore, it balances the importance of impact reduction and fast recovery using functionality as a metric, but avoids specifying the source of the disturbance. It has some analog with most of the suggested definitions in the literature. However, these variations are always in the same atmosphere and consist of different combinations of the components mentioned in Fig. 1.

1.2 Why We Need Resiliency?

A different design approach that considers the possibility of failure: In most engineering practices, we design to avoid failure. However, this strategy or mentality is destined to fail, especially under the changing environment and the emergence of new threats. Using safety factors and load multipliers gives a sense of excess capacity and apparent immunity to the system. However, these factors provide acceptable reliability levels. So basically, we are admitting the possibility of failure as inherent truth with no strategy to deal with it in the traditional design mentality.

The fact that our current design process relies on historical records or experiences, even fuel this problem. For example, using historical precipitation records, we can estimate the amount of water gathered behind a dam and use this to calculate expected energy production. However, the effects of unprecedented changes in precipitation patterns caused by global warming and climate change can alter these calculations. Even more, the lack of representativeness and reliability could lead to substantial economic and social costs. In resiliency-based design, we accept the possibility of failure and design the system to reduce the impact of such failure and make the recovery process as smooth and fast as possible.

Disaster cost reduction: The cost of a disaster extends to several aspects, including the economic, environmental, and human capital, in other words, the three bottom lines of sustainable development. System resiliency focuses on impact reduction and fast recovery. Therefore, resiliency reduces the cost of disturbances on these capitals and fosters sustainable development. Moreover, several resiliency assessments and enhancement methods use the cost-saving for one of these capitals as a metric.

The complexity and interdependency of the modern city system: The developed cities' supporting systems are growing more complex than ever to ensure the well-being and thrive of their population. However, rapid urbanization and the accelerated integration of smart technologies incite these challenges [10]. Technologies like electric cars, for example, need huge infrastructure to support it and can cause shifting in electricity consumption patterns. These evolutions were not considered in the past development plans and can be costly and time-consuming. Mobility reliance on electricity means any disturbance in the electrical network will have severe consequences on the transportation network. The cost and damage of this rippling failure across interdependent systems could be higher than the direct one on the original failed system [11].

2 Resiliency in Electrical Systems

Electrical networks are the most critical system necessary for any modern city or even any sort of modern life. Electricity powers almost all the equipment that we use in our daily life. Losing electricity would severely threaten our ability to provide water, communication, and many other essential services, even in large cities. Furthermore, the associated damages and costs would be extremely high.

Electrical networks consist of three main stages: generation, transmission, and consumption, each with different levels of resiliency. Each stage of the electrical network has distinctive characteristics and is exposed to a specific set of threats. These distinctive properties cause different levels of resiliency, but all stages affect the overall network performance. However, the most exposed part is the transmission lines, which typically have the most impact on the system resiliency [8]. Also, the adaptability of other components to changes in the network could affect the resiliency [12].

Electrical power networks typically are protected against regular and possible reoccurring problems through several expert-based strategies and proper maintenance and operation practices. These practices could provide a sense of reliability and security. However, we must consider the changing world we live in and emerging threats and disasters that rendered huge investments and capital as null. For example, in 2003, a power outage hit the USA and Canada, affecting 50 million customers, with the estimated economic loss being about $6.4 billion. In the same year in Italy also, a power outage affected 56 million customers, and the economic loss estimated was $120 million [13–15].

Some of the main properties that make the electrical systems exposed are

- Physical constraints associated with energy production and distribution where power is not easily stored, rerouted, or redistributed like traffic in transportation systems or flow in a water network.
- Electrical distribution systems have been widespread in a way that makes it almost impossible to protect all its assets and parts.
- Most of the high-impact disruptions in the electrical network (more than 80%) occur in the distribution side rather than generation facilities, which are easier to reinforce, maintain, and replace.
- The renewable sources still lack in reliability. Renewable sources could provide support for the network during disasters and peak demands. However, they are less reliable because of the effect of wind speed and solar radiation on their production, for example.
- High vulnerability to climate change imposed disasters. An increase in wind and thunderstorms strength could affect transmission lines and substations. Even more, a change in surface water temperature can affect generation capacity, especially in nuclear reactors. These are just examples of climate change phenomena that can seriously damage electrical networks.
- It is hard to finance the replacement of aged infrastructure. Many believe that replacing an aged but functional component of a network is an unnecessary cost.

2.1 Electrical System Resiliency Representation

Drawing a relation between system performance and time during an event could quickly reflect many properties of the system. For example, it can help identify prolonged stages or even quantify resiliency by the area of reduction, as shown in Fig. 2.

Researchers have developed many performance representations for different systems, depending on their nature and response toward the disaster. The most notable representation is the “resiliency triangle” used to assess and quantify it based

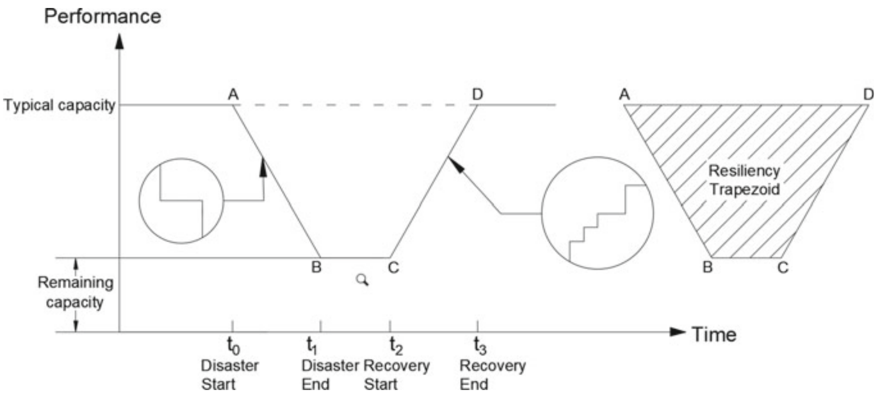

Fig. 2 Behavior of a power system and resiliency trapezoid. This figure presents the expected performance of an electrical system during a disturbance. We can notice two details presenting the discrete nature of equipment and assets failure and recovery in a cascade failure from the system point of view. It is also worth considering that massive blackouts of a cluster (caused by losing the main link) could cause converting (AB) to vertical line shape, for example.

on system performance [16, 17]. Nevertheless, in the case of electrical systems, it would be more accurate to represent it with a trapezoid, as presented in Fig. 2.

3 Some of the Resiliency Assessment Methods

The resiliency assessment methods vary in complexity and are affected by many factors. Here we will present three assessment methods adopted in the research. These methods are, namely, topological method (the most straightforward), flow-based method (the most realistic), and game theory (the most suitable for intentional attack modeling).

3.1 Topological Method (Complex Network Analysis)

This method is widely used and considered one of the most effective yet simple methods to assess electrical network resiliency. This method initially started in social studies to represent the relationship between various entities or people and was later applied to critical infrastructure assessment [18–22]. It also forms the base that other methods like logical or optimization used to resemble the network [23]. By schematically drawing the system representing important parts as nodes like substations, poles, and generation facilities, and the links drawn between them like transmission lines, as in Fig. 3.

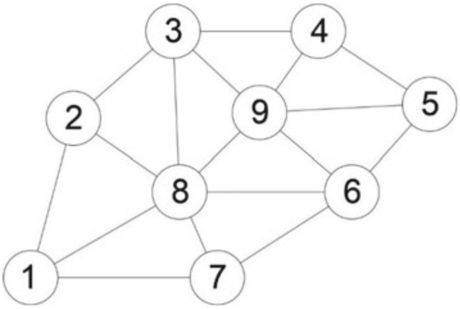

Fig. 3 Example of network representation

This schematic representation of the network reflects the relation between various components, also referred to as the graph. It facilitates extracting valuable information like identifying critical nodes. The most straightforward centrality property is the node's degree, which is equal to the number of connections of the node and reflects the closeness to other nodes. The other most commonly used property is betweenness, which reflects the role of the node in connecting other nodes in the network.

Typically, researchers conduct resiliency assessment, in this method, by observing the results of losing links or nodes. They would select the removed elements based on their geographical location, centrality, or random selection [2, 24]. However, we can observe two primary types of modeling approaches: pure models and extended models.

In the pure modeling approach, the graph presents the topological distribution of the elements and their connections in the network. However, this representation of the network disregards the physical constraints or flow direction [25]. This assumption simplifies defining and analyzing processes allowing for faster results. However, using topological properties only as a resiliency indicator could be misleading [26].

On the other hand, extended graph models aim to provide a more realistic representation of the system. By integrating real system properties and information, the assessment becomes more accurate [27]. Researchers apply this integration by assigning weights to links or nodes. In links, this weighting could reflect resistance, voltage level, or associated losses. On the other hand, weighting in nodes could reflect generation capacity, number of customers, or served load [28]. This approach allows favoring high-value parts in the topological analysis. Subsequently, this favoring increases resiliency assessment sensitivity [24].

3.2 Flow-Based Methods

This method simulates the performance of the electrical network accurately but demands massive computational resources. This method relies on the mathematical formulation of electrical energy flow equations and laws. These equations have two primary solution approaches:

Deterministic approach: Finding a steady-state solution is the aim of the deterministic approach. The effectiveness of this method is related to the type of current in the system. Alternative current flow equations have nonlinear nature. So, the solution is through iterative methods like Newton–Raphson. This iteration is high resource-demanding, which limits its applicability for large-scale simulations. On the other hand, converting AC into DC can allow linearizing these equations. This approximation could reduce the resources required significantly. For solutions to these equations, readers can refer to [29].

Probabilistic approach: This approach accounts for the dynamic nature of the electrical system. The probabilistic approach considers changes in generation capacity, load, or network configuration. Even more, this flexibility makes it suitable for resiliency assessment for conventional networks and renewable supported ones. The solutions in this approach use simulation or analytical methods, like Monte Carlo simulation and linear approximation [30].

3.3 Game Theory

Game theory model the impact multiple external actors have on the network. Because it models the interests of several influencers, game theory typically suits intentional attack scenarios. Two main types of games exist within this method: competitive games and cooperative one. The competitive one is typically used to model the attacker/defender scenarios [31]. This game aims to maximize the payoff value for each side regardless of the other side's choice, which is called Nash equilibrium [32]. The cooperative game aims to determine how to distribute a collation profit on its contributors, denoted as Shapley value [33, 34].

One limitation of this method is scalability. However, one way to overcome this limitation is by combining it with the topological method. For example, Cheng et al. [35] used Nash equilibrium to model an intentional attack on an electrical system and identify the best defense strategy. By applying this method on a large-scale test system graph, they could simplify the process and reduce the elements to a limited number of links and nodes. Furthermore, they made a better-informed identification of the critical link than the original graph method. Nevertheless, cooperative games can lead to the distribution of the resources on the links based on their role in the resiliency of the system [34, 36, 37].

4 Case Studies

In this part, we will present two real-life cases. The first case reflects the cost of a low resiliency grid. On the other hand, the second case presents technology employment for electrical grid resiliency assessment and enhancement.

4.1 Case Study 1: PG&E (Pacific Gas & Electric), USA

PG&E is the largest energy utility company in the state of California, with almost 18 million customers. In the past decade, several wildfire disasters struck the state, most notably in 2017 and 2018. In 2017, Tubbs Fire burnt almost 145 km^2, destroyed 5,600 buildings, and claimed the life of 22 persons [38]. The next year, the Camp Fire spread across Butte county, causing far more damage with a death toll amount to 86 persons and a destruction of 19,000 buildings [39]. California Fire department assessment found the company responsible for the disasters. Their report claimed that the company has committed grave mistakes regarding network maintenance and did not fulfill safety requirements. Even more, the report pointed out that some equipment is outdated, and vegetation clearance precautions were not enough [40]. After a lengthy case in the court, the company plea guilty, with an estimated liability of $30 billion [41]. With this considerable bill, the company decided to file for bankruptcy [42].

Some researchers described this case as the first climate change bankruptcy. They claimed that this series of disasters is a clear result of climate change and the lack of preparedness toward its impacts. They stated that prolonged drought seasons and a rise in temperature played a vital role in these catastrophes. These phenomena are associated with climate change. They also noted the insufficiency of current safety regulations to protect against climate change impacts, added to the deteriorating status of the equipment, are the main reasons [43].

In response to these tragic events, PG&E started implementing several practices and strategies to increase the resiliency of its network. The company launched the "community wildfire safety program" to protect lives, properties, and the environment from such disasters and increase the resiliency of the grid. This initiative includes improving inspections and safety practices for more than 24,000 km of power lines in high- to medium-risk areas. Also, it includes improvements to the network through undergrounding, shifting to microgrids, upgrading the equipment in the network, and adopting stricter limits than mandatory vegetation clearance regulations. Furthermore, they installed improved surveillance systems with HD cameras and dedicated operation centers for continuous monitoring and coordination [44].

This series of catastrophic events shows how climate change impacts, coupled with malpractices, could be costly. Climate change, through the increase in rates and intensities of disasters, is rendering the previous practices or strategies as null. We need to improve our design mentality and focus more on resiliency approaches to ensure system continuity and prepare for the failure of the system. Even more, we should account for the dynamics of the changing world/environment that the system exists in [45, 46].

4.2 Case Study 2: National Grid, USA

National Grid is a multinational company serving more than three million customers across five states. In 2003, the company decided to perform a vulnerability assessment for its assets toward floods. This assessment was performed by using a Geographic information system (GIS). They overlay the network layout with Flood Insurance Rate Maps (FIRMs) published by the Federal Emergency Management Agency (FEMA). The resulted map could indicate substations belonging to each type of flood zones. Based on these results, they divided the substations into three risk categories high, medium, and low associated with 100-year, 500-year flood zones and outside them, respectively [43, 47].

This classification allows laying out a plan to enhance the resiliency of the network both in the short term and long term. Short-term enhancements include elevating the equipment and adding barriers while the long-term strategies like relocating substations and redesigning the network will be implemented. The classification facilitates resource allocation and endangered assets prioritization [43, 47].

This case shows how utility companies can capitalize on an innovative approach to enhance the resiliency of their networks and resource allocation. The integration of GIS into strategic planning could foster network resiliency, reduce the cost of maintenance, and the occurrence of service disruptions. Classification and prioritizing of endangered assets is a cost-effective approach compared with random enhancement or whole-system reinforcement.

4.3 Renewable Energy and Resiliency

Renewable energy sources are popular elements of sustainable development plans concerning the energy sector. Environmental concerns, governmental incentives, and the rise of oil prices promoted the adoption of renewable energy sources as a clean and cost-effective alternative to conventional fossil fuel sources. However, despite enormous interest and research funding to develop these technologies, they are still far from providing continuous, reliable, and cost-effective (without incentives) sources of energy [48, 49].

The main challenges facing renewable resources are related to energy storage and generation stability. Energy storage technologies still suffer from capacity degradation after a certain number of charge/discharge cycles and temperature limitations for fast charging [50]. On the generation side, solar panels rely on daylight availability, and its production could significantly drop during winter [51]. However, solar panel production is far more predictable compared with wind turbines. For example, one study observed that the increase in wind speed reduces the resiliency of the network due to an increase in speed variation [52].

However, renewable energy sources can enhance the overall conventional network resiliency. Resiliency in energy systems is all about reliability and continuity of service. So, by applying microgrid and islanding strategies during outages, we could meet isolated clusters' demands through balancing renewable energy sources production and storage unit capacity [53]. This employment of renewable and storage technologies allows service continuity during disasters and disruption in the main network, thus increasing the resiliency of the network [54, 55]. This integration is highly crucial in remote areas or island states to boost its resiliency and sustainable development [56].

4.4 Strategies to Enhance the Energy System Resiliency

Enhancement strategies of energy systems resiliency vary depending on the effectiveness, the allocated resources, and the nature of the anticipated threat. However, we present some strategies based on threat type, as in Table 1.

4.5 Challenges Facing Energy Systems Resiliency

The main challenges faced by electrical systems resiliency are

1. Develop a consensus about resiliency definition and a specific set of indicators that could allow for a fair comparison of different alternatives. Unlike the current situation where researchers are still proposing different interpretations that could provide incomparable results.
2. Increase the awareness regarding climate change impact, moving from mitigating to accepting it as reality, and develop simulations to assess its impact and incorporate it in design practices.
3. Aging infrastructure, despite achieving many advancements in the past years, many countries are still relying on decades-old infrastructures and technologies, especially in power networks. The false feeling of security or necessity is hindering the much-needed network modernization. These upgrades would recover the network from its deteriorating status and improve its resiliency.
4. Financing: during the pre-disaster period, people tend to feel safe and take electrical network continuity for granted. So, justifying the huge investment to reinforce and upgrade the grids and to finance resiliency improvements is a hard mission. Nevertheless, in the post-disasters period typically, the enormous cost of the disaster puts a significant strain on the budgets, which limits the capability

Table 1 Resiliency enhancement strategies

Threat	Resiliency enhancement strategies
Floods	Relocate critical links and assets outside flood-prone areas
	Elevate equipment above 500 years return flood datum
	Use durable and corrosion-resistant material (like stainless steel or fiber-reinforced polymers) in parts and components exposed to floods
Storms	Reduce the distance between overhead lines poles to increase their resistance toward windstorms
	Burying transmission lines (if the area is not prone to flooding)
	Use lightning arrestors to protect assets
Wildfire	Provide and maintain a safe clearance of transition lines from surrounding vegetation
	Use components made of materials with high thermal stability and fire resistance
	Equip critical assets surrounding with sprinklers and fire control system
	Install fire alarm systems and coordinate with the local fire department to ensure rapid response and necessary measure implemented
Cybersecurity	Diagnose the control system to address cybersecurity concerns
	Prepare troubleshooting plan in case of firewalls penetration
General	Replacement of aged equipment and continuous evaluation and maintenance
	Adopting advanced technologies and strategies like microgrids, energy storing and renewable sources, and smart switches and meters to increase efficiency and management of the system
	Using "safe to fail" design approach resiliency should be part of the design and delivery process to limit cascading failure
	Include resilience costs in service rates to encourage resilience enhancements
	Identify critical assets and equipment and ensure the availability of a fast replacement and effective maintenance
	Provide incentives and encourage decentralized energy production to ensure inherent resiliency and service continuity after disasters
	Install alternative links for critical bottlenecks in the network to be used as a rapid substitute
	Assessing different circuit topology and choose the suitable one for the intended level of resiliency with consideration of the cost of over the life cycle

of upgrading the network based on lessons learned. However, one thing decision-makers should bear in mind is that the cost of upgrading is far less than the cost of a disaster. For example: in the wake of the Fukushima nuclear disaster, nuclear-regulating agencies developed additional safety measures to avoid similar future disasters. Applying these measures worldwide could cost around $47 billion, which is a considerable cost. However, the cost of the disaster is $180 billion and 40 years to recover the area according to Japanese estimations [43].

5 Resiliency, Interdependency, and Nexus

Critical systems share the same spatial space, mutual dependencies, and consequently contribute to the overall city's resiliency. The interdependency of critical systems and their existence within the same spatial spaces make them affected by various disasters with different levels of impact per system. However, the damage sustained by one system may threaten the stability of another interdependent system. The propagation of failure from one system to another highlights the importance of addressing the mutual security of the systems, also known as nexus, within resiliency scope [1].

The term resiliency has a different interpretation and metrics in different fields and systems, depending on their nature. However, in most cases, it converges at two points that are minimizing functionality disruption and the swift return to the normal situation. This aim has many reflections in the design and operation of various systems, especially when trying to address questions like resilience to what. In this section, we will address some examples of systems relations and their effects on the resiliency [9].

5.1 Energy and Water

Serving the vast concentration of population in cities with clean water requires energy-intense processes. Energy supply is essential to the artificial water cycle. The artificial water cycle includes pumping of the untreated water from its sources, treatment, pumping toward consumers, and finally collecting and treatment of wastewater. This chain of processes stretches throughout cities and even sometimes starts or ends at distant sites, which could consume a massive amount of energy. Treatment facilities use several techniques to ensure the quality of supplied water, which could consume a considerable amount of energy, especially in the case of ultraviolet and ozone treatments [57, 58].

Water desalination is the primary source of water in some regions of the world, which makes water supplies even more dependent on energy. Water scarcity is a challenge facing many countries, especially in the GCC area, which forces them to rely on desalination. Desalination technologies, in general, are energy intensive [59]. However, some researchers are trying to formulate the process to make it more efficient and rely on solar energy as a renewable source [60]. Furthermore, this technology is still not mature enough and unable to provide stable and continuous production, but we can enhance its reliability and resiliency through integrating voltage controller and storage system [61].

In return, water resources can produce energy if appropriately managed through hydraulic dams. Dams are a great example of converting water resources into energy production. However, proper management and planning are necessary for the continuity and reliability of energy production, especially with repetitive droughts seasons caused by climate change. The declining water levels in Lake Mead behind the

Hoover dam are threatening Las Vegas' electricity supply and food production in the area, for example, due to accelerated drought cycles linked to climate change [62].

5.2 Built Environment and Energy

Buildings are responsible for a considerable part of energy consumption, which is essential to provide services and comfort to occupants and the functionality of the building. Typically, engineers, during the design process, not only address the resiliency of the structural components but also for non-structural components. Non-structural components include HVAC and lightening systems, among others. So, in order to deem a building resilient, engineers must ensure limited damage and restoration of the functionality of these supporting systems to get the building back in service. Structural resiliency should also extend to consider the status of supporting infrastructures, which can affect the downtime and play and impending factor [63].

Buildings should include passive and active strategies to enhance their resiliency. Buildings' envelop, orientation, and design affect occupants' comfort, energy consumption, and consequently its resiliency. These practices improve natural ventilation and thermal survivability during outages protecting the most vulnerable like elders [64]. Integrating an on-site power generation and storage system helps enhance resiliency as an active measure. Some researchers simulated the concept of a "building as a power station," where they relied on renewable sources and storage equipment to produce all energy needs isolated from the network [65].

Energy-efficient buildings can enhance the electrical network. Strict building regulations like imposing high insulation requirements and power-efficient appliances can reduce the load on the network and decrease the peak demands. Furthermore, maintaining the structural integrity of energy components could effectively increase its resiliency [66].

5.3 Energy and Transportation

Transportation system efficiency is essential for the thrive of the city and contributes to its resiliency but also affected by disturbances in the energy system. Well organized transportation network can boost the growth and well-being of the city population during a normal situation. Even more, during a disaster, it provides mobility for restoration activities of other critical systems. However, various transportation methods rely on energy supplies. For example, most of the vehicles consume fossil fuel to power their motors making them vulnerable to fuel shortages [67, 68]. Also, metro and trains, which provide services for hundreds of millions worldwide, rely on electricity as a power source, and this leaves it exposed to failures in the electrical network [69, 70]. On the other hand, the transportation network can ensure the mobility of maintenance teams, resources, and equipment needed to keep the energy network running.

Another agent that started to affect the integration between transportation and electrical networks is electrified cars. The increase in efficiency, reliability, and safety of electric cars combined with a rise in environmental awareness has contributed to accelerating the adaptation of these vehicles. Some researchers are arguing that the increased penetration of this type of vehicle can jeopardize the resiliency of cities and transportation networks and increase the load on the electricity network [68]. However, other researchers have suggested the use of these vehicles as mobile energy storage, allowing them to provide support for owners' property. Even more, this application will allow transferring energy from the primary backup source provided by the municipality to increase the city's energy resiliency during outages [71].

6 Conclusion

In this book chapter, we examined the resiliency in the energy system as an essential design approach under changing circumstances and rising challenges. Resiliency has various definitions that agree with limiting the system degradation and regaining functionality within an acceptable period. Resiliency assessment methods vary depending on the available information, allocated resources, and the purpose of the assessment. Islanding, microgrids, and renewable energy applications can enhance network resiliency during outages. However, due to unstable renewable energy production rates and limitations in the available power storage technologies, a complete decentralization of energy networks is not achievable yet. Nevertheless, decentralized energy production would highly improve resiliency.

Cities are a system of interdependent and integrated systems. This integration and mutual dependency allow various critical systems to work efficiently and ensure the well-being of the population. However, they also allow failure in one system to propagate into others, especially the energy system, which allows the functionality of other systems. Resiliency planning should address these relations and the resulting nexus to develop a resilient city.

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Environmental Impact Associated with the Performance of Building Integrated Photovoltaics: Life-Cycle Assessment Perspective

Saoud A. Al-Janahi and Sami G. Al-Ghamdi

Abstract Solar power can be used as a clean and sustainable source of energy that can in turn be applied in many ways, including to buildings; solar power applied to a building can produce energy for use directly inside the building. Solar Photovoltaics, which are directly attached to the building, are called Building-Integrated Photovoltaics (BIPV). This type of Solar Photovoltaics is considered a main constructed layer of the building as it can replace the Façade, windows, or rooftops. Nevertheless, to manufacture BIPV, the manufacturing process consumes an abundance of energy and produces an extensive amount of greenhouse emissions. These energies and emissions are either directly related to the processes of manufacturing BIPV or they are indirectly related to it—through the fossil fuels burnt to produce the energy that manufactures BIPV. In this case, a Life Cycle Assessment (LCA) will be conducted to quantify the emissions and waste associated with the manufacturing processes or the energy that is needed as an input to these processes. An LCA can be used to indicate all types of impact categories associated with the whole life cycle of the product, in this case BIPV. This chapter describe the environmental impact associated with the performance and the manufacturing of BIPV based on an LCA. Through a review of multiple types of studies, this chapter focuses on the environmental impact of the different types of material, like silicon and thin-films, used to manufacture BIPV. Different applications of BIPV are also considered as a means of assessing the performance of BIPV when applied to different layers of a building as well as the environmental impact performance when BIPV operates in different geographical locations. As a comparison, Energy Payback time (EPBT), which plays a key role in understanding the energy break-even point for the used BIPV, will be examined as well.

Keywords Life-cycle assessment · Building integrated photovoltaics · Environmental impact · Payback

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S. A. Al-Janahi · S. G. Al-Ghamdi (✉)
Division of Sustainable Development, College of Science and Engineering, Hamad Bin Khalifa University, Qatar Foundation, Doha, Qatar
e-mail: salghamdi@hbku.edu.qa

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1 Introduction

Building-Integrated Photovoltaics (BIPV) operate in buildings as an electricity input. It is installed into a building's envelop as part of the structure. BIPV can replace skylights, rooftops, façades and windows [1–3]. The main advantage of having BIPV in buildings is that it can provide clean and efficient energy as well as contribute to a building's aesthetics [4, 5]. However, before claiming that BIPV provides a clean source of energy by transferring solar energy into electrical, the manufacturing processes and the environmental performance of BIPV must be considered. There are multiple burdens associated with the environmental performance of BIPV [6, 7]. In this regard, a Life Cycle Assessment (LCA) study can help to determine the most appropriate way the environmental impact and burdens for each process associated with the manufactured or operated BIPV. This determines the break-even point for the Energy Payback Time (EPBT) wherein the operated BIPV produces the same amount of energy that it took to manufacture and use it [8]. In this chapter, then, the different types of BIPV and the environmental performance as determined by the LCA are discussed in order to compare their environmental impacts.

1.1 Building-Integrated Photovoltaics (BIPV) System Description

Building-integrated Photovoltaics (BIPV) is a solar system of energy that produces electricity that the solar PV panels directly integrate with the building envelope and replace the main building's components like the normal façade—which can be replaced with BIPV's PV solar façade [5, 9, 10]. Thus, PV technologies, and BIPV in particular, are the most efficient tools available for utilizing solar power. BIPV products transform the building from energy consumer to energy producer [11, 12]. As BIPV replaces main building components, it needs to fulfill some of the tasks those components perform, like the building envelop for energy reduction, the day-lighting and noise reduction [13]. This can be achieved by combining BIPV with types of glass (i.e. insulation glass) [10, 14]. There are multiple types of technologies used for BIPV, the principal ones being crystalline and thin film modules technologies [9]. In addition, BIPV can be classified into systems: solar battery or grid-connected BIPV. Grid-connected BIPV acts as infinite storage for the electricity produced by BIPV. Additionally, BIPV can be characterized into three main types: PV technology (material) whether they are silicon or non-silicon based, application type such as roof and facade, and market names [5]. In this study, the main types that will be considered for comparison are PV technology and application type; this is because the comparison will be based on concrete differences as opposed to market names, which are more likely to be named according to market products. Shukla et al. [12], though, claimed that Building-Applied Photovoltaics should be considered a type of BIPV.

1.2 Environmental Performance Relation with BIPV

Although BIPV is considered a clean producer of energy because it transforms sunlight into electricity, it wastes and consumes a considerable amount of energy while extracting, manufacturing, transporting, using, and wasting BIPV [15]. This means that the Life Cycle of the product itself should be considered in addition to the usage phase [16]. Therefore, a Life Cycle Assessment should be conducted in order to analyze the entirety of waste and emissions associated with the Life Cycle of the product. Such waste and emissions are considered direct if associated with the manufacturing process and indirect if they were caused by physically toxic fossil fuels used in the processes of the waste and emissions [3, 17]. As a result, evaluating the energy payback time (EPBT) becomes necessary in order to locate the break-even point: when the product's ability to produce clean energy equals the energy wasted during manufacturing. Another parameter to consider is which type of BIPV generates more Greenhouse Gas Emissions (GHGE) during its Life Cycle [12].

1.3 Objectives and Scope

The principal reasons for applying BIPV to practical life and using LCA as a tool to quantify environmental impact are to reach optimum usage of energy resources and to prevent waste and pollution. BIPV helps to produce clean and efficient electricity; this ensures stability and can lead to the conservation of other energy sources for use by future generations. Moreover, an LCA is necessary because it provides a method for quantifying the environmental impact and burdens of BIPV through its life cycle by evaluating the EPBT, GHGE, and other environmental impact categories. The objective, then, is to know and understand how to mitigate the environmental impact and burdens associated with the life cycle of BIPV in order to have the most optimal, environmentally friendly product.

An LCA can be used to evaluate the types of BIPV for different applications, meaning it can aid in making decisions about the most efficient and clean type of BIPV for a given circumstance. In this chapter, multiple types and applications of BIPV are reviewed and discussed in regard to their life cycle and environmental impact.

This chapter is outlined under two main divisions: (1) an LCA of solar BIPV regarding the main types of material used and (2) the geographical location of the applied BIPV. The first division will be divided into silicon-based and non-silicon-based reviews, while the second division will be about the environmental performance of BIPV in different locations around the world.

2 Life Cycle Assessment

The Life Cycle Assessment (LCA) is a tool used to assess the environmental impact associated with a certain product or system throughout its life [18, 19]. An LCA is composed of four main stages: goal and scope, life cycle inventory analysis, life cycle impact assessment and interpretation [19, 20]. An LCA must be performed according to ISO standards to ensure that its sufficiency. ISO 14040 and ISO 14044 are defined frameworks for carrying out an LCA study. ISO 14041, ISO 14042 and 14043 are the standards that should be followed in the four main stages of an LCA: goal and scope definition, inventory analysis, life cycle impact assessment, and life cycle interpretation, respectively [8, 19, 21]. The stages are shown in Fig. 1 [20, 22, 23].

1. Goal and Scope: In the goal and scope stage, the purpose of the study should be defined to set the system boundary and to fix a functional unit [19, 24].
2. Life Cycle Inventory Analysis (LCIA): This is the second stage where all the data will be collected and where elementary flows (inputs and outputs) of energy, water, materials, wastes and emissions for the whole system will be quantified in relation to the functional unit [19, 24].
3. Life Cycle Impact Assessment (LCIA): The environmental impacts and wastes are classified and characterized into environmental problems such as global warming, ozone depletion, acidification, and toxicity [19, 24].
4. Interpretation: This concludes and summarizes the results of the LCI and LCIA, indicating the most important points and analyzing the required critical environmental impacts. The results should include recommendation and future improvements for the system [19, 24].

Generally, an LCA can help determine the processes that generate the most waste and produce the greatest amount of emissions. It can also help the intended audience make the most informed decision in terms of how best to decrease the harmful environmental impact.

To attain the desired results from the study, the correct goal should be decided in the goal and scope stage; the full data needed to conduct the LCIA, the correct

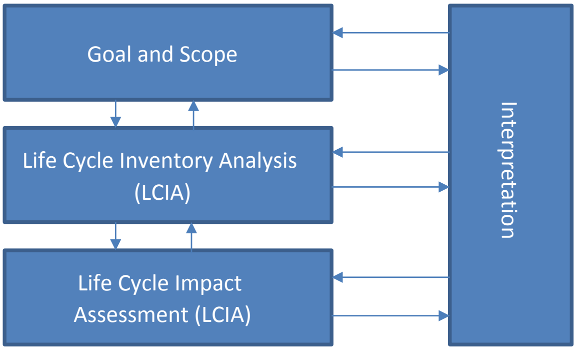

Fig. 1 The formwork of life cycle assessment (LCA)

environmental impacts and categories, need to be formulated at the conclusion of it in order to present the results and the outcomes of the entire study. However, the results should focus primarily on uncertainties in the analysis like data uncertainty and variability as a way of comparing the conflict between the true value and the values of the measured quantity [25, 26].

Usually when conducting an LCA study, software is used to integrate the many processes involved in order to maintain the quality and quantity of inputs and outputs. The best-known LCA software are Gabi, SimaPro and GREET. Well-known Impact assessment methods, including CML 2001, Eco-indicator 99, TRACI, and ReCiPe, have also been developed as ways to represent the results [27].

2.1 *The Relation Between Life Cycle Assessment and Solar BIPV and PVs*

Solar PVs are widely considered a clean and sustainable source of energy because they do not emit and because they operate in a clean manner. However, deeper analysis can give different results; namely, it can determine which life cycle assessment is able to analyze the life cycle of the whole system from cradle-to-grave. It is true that the system can be considered an absolutely clean source of energy, but it does consume massive amounts of energy and emit enormous amounts of wastes during the period where the PV materials are extracted and manufactured [28]. An LCA study can, then, be implemented in order to quantify this consumed energy. After the LCA is conducted, the EPBT is calculated to determine whether the system produces enough energy to equal the amount of energy consumed during its fabrication, construction, and decommissioning stages—a distinction that would qualify the energy as clean and provide the most substantial benefit to the environment [29]. The stages of the LCA that most PVs undergo are shown in Fig. 2 [30].

It is most common that PVs have no impact or emission during their operation phase and that the highest rates of energy consumption and emissions occur during the fabrication and construction phases. For example, two studies conducted can illustrate that the most energy consumption and as a result produces greenhouse emissions are within these three phases as illustrated in Table 1.

For the Rooftop system, the construction phase involved the construction and fabrication of the PV system as well. The negative sign for the decommissioning phase is that it will contribute toward GHGE saving for future usage [30, 31].

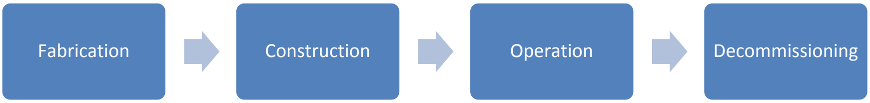

Fig. 2 Life cycle stages of regular PVs

Table 1 The breakdown of the GHGE of LCA stages for Solar PVs (%)

System	Fabrication	Construction	Operation	Decommissioning
Rooftop type PV (3 kW) [31]		76.9%	23.1%	–
Mean GHGE of Solar PV systems reviewed [30] (%)	71.3	19	13	−3.3

The impact categories associated with an LCIA that are most closely related to PV systems are EPBT and GPBT. In addition, global warming potential (GWP), ozone depletion and human toxicity are metrics used to assess both impacts on the environment and the effectiveness of the PV system; they can also predict the amount of time the system requires to start producing more energy than what required to fabricate the PV system as well how many greenhouse emissions the system will save when compared to emissions associated with the manufacturing phase [32, 33].

3 LCA of Solar BIPV Regarding Main Types of Material Used

BIPV can be made using different materials that fall into two main classifications: silicon-based BIPV and non-Silicon-based BIPV [2, 5]. It is also classified into silicon and thin films types, though there are thin films types that are manufactured with silicon [34]. Therefore, in this chapter any BIPV made with silicon will be treated as silicon-based and any BIPV not made with silicon will be considered non-silicon-based.

3.1 Silicon-Based BIPV

Lu and Yang [35] reviewed a flowchart of processes that were used to manufacture silicon-based PV. They indicated a general processes flowchart of mono-Si, multi-Si, or a-Si. A brief description of the flowchart is described by them. Firstly, silica sand is extracted and purified into EG-Silicon (metallurgical grade silicon). The MG-silicon needs to be further purified into EG-Silicon (electronic silicon) or it can be purified into SoG-silicon (solar-grade silicon). The purification processes happening in chambers of a reactor where gases (hydrogen and trichlorosilane) are heated to 1100–1200 °C. In the modified processes, the hydrogen and trichlorosilane are heated up to 800 °C, which can save a substantial amount of energy and in turn can mitigate the environmental impact. A flowchart of system boundaries from cradle-to-gate of manufacturing a silicon-based product is illustrated in Fig. 3 [22].

Fig. 3 Cradle-to-gate flowchart of Silicon-based solar cell

Several studies have demonstrated the impact of manufacturing silicon-based BIPV and how much energy can be gained out of the manufactured BIPV system. One such study examined a 40 kWp BIPV system installed in Newcastle that was supplied by a BP Solar company from Spain and manufactured from Mono-Crystalline Silicon (m-Si) [16]. This system is expected to generate 600 MWh over its entire lifetime, which will span 25 years. It will be used as a façade in a covering area of 390 m^2. The total energy required for its life cycle and its balance of system (BOS) component is 165,868 KWh. The energy payback time (EPBT) for the system would be 6.9 years, which means that the system will be able to save waste and emissions for more than 18 years after the EPBT. Another BIPV system, this one made from Mono-Crystalline Silicon, was manufactured and operated in Hong Kong [35]. The capacity of this system is 22 kWp and it is a rooftop-applied BIPV. There are 126 cells of Mono-Crystalline silicon cells installed in this BIPV system. The total Energy required (embodied energy) for the life cycle of this BIPV system is 205,815.5 kWh, which means that 29% (59556.45 kWh) of this energy is for the BOS of the product and nearly half of the embodied energy goes to silicon purification processing (46%). Regarding PV fabrication, Silicon slicing, and transport are weighted at 15, 8, and

2% from the overall percentage. The annual solar radiation received from weather data between 1996 and 2000 is 266,174 kWh; the energy output will be 28,154 kWh, as the efficiency of the system is 10.6%. The EPBT will be 7.3 years and the lifetime of the system is assumed to be 20–30 years. The study claims that if PV is installed as façade, the EPBT will be much longer as the irradiance will suffice as a rooftop for the selected building. It is estimated that the greenhouse gas payback time, or the greenhouse gases emitted during PV system fabrication, is 98,834 kgCO_2eq. The annual greenhouse gases saved from the power station is 28,154 kWh × 671 g/CO_2eq, which is equal to 18,891 kg CO_2eq. Therefore, the Greenhouse Payback Time (GPBT) is assumed to be 5.2 years. A UK study done about a BIPV made of Mono-Crystalline Silicon that will be installed in roof with a capacity of 2.1 kWp [36]. The goal and scope of this study were explained to examine the impact of BIPV in the UK and the functional unit set to be "a 2.1 kWp mono-crystalline BIPV roof tile system installed in new build property and connected to the UK national grid with a lifetime of 25 years." The software aiding this study were Simapro 7.1 and Ecoinvent V2.1, used as databases for inputs and outputs. The results showed that 45% of the embodied energy contributed to PV cells of crystalline silicon, which required intensive energy. Other processes that consumed energy are frame, which consumed 20%, tedlar film, which consumed 13%, inverter 2.5 kW, which consumed 8%, transport, which consumed 6%, glass, which consumed 3%, electric installation, which consumed 3%, and miscellaneous, which consumed 2%. The total embodied energy for this system was 83 GJ and the EPBT is estimated to be 4.5 years. Life cycle impact categories were extracted by using Eco-indicator 99. PV cells contributed the largest portion extracted mainly because of the intensive energy needed for silicon purification. This BIPV system embodied 4500 kgCO_2eq greenhouse gas emissions. However, the total savings over the 25-year lifetime will be 22,400 kgCO_2eq, making the GPBT around four years. Another study, this one of a Poly-Crystalline Silicon (p-Si) BIPV system, assumed that the BIPV system was replaced with conventional glass cladding. The conventional glass cladding assumed to be 10 mm thick where the thickness is applied to BIPV system. The system requires 2.9 MJ of embodied energy to supply each 1 kWh of electricity. In the same study it was assumed that the embodied energy of the BIPV system can be reduced to 2.6 MJ of energy for each 1 kWh of electricity if the burden of the conventional glass cladding is deducted from the burden of the BIPV system. In addition, the study compared the BIPV system against PV plants and electricity in European countries and it was observed that the BIPV system showed great attitude, where the energy used to manufacture the system was lower than the mentioned systems. This is mainly due to the required manufacturing of massive amounts of BOS components that will in turn require large amounts of energy. This study also assumed that the electricity generated by BIPV will be used in the building, meaning there is no need for any transmission components. This case will be applied to most of the studies since the electricity demand will be higher compared to the electricity generated by BIPV in most cases. The study compared the EPTB, lifetime, embodied energy, and energy saved both in BIPV as an independent system and BIPV if the burden of the conventional glass cladding is deducted from the burden of the BIPV system (net BIPV) [14], as can be seen in Table 2.

A study conducted by Huang and Yu [37] compared three different silicon materials: single-crystalline silicon, multi-crystalline silicon, and amorphous silicon cells, which are fabricated to be BIPV applications. This study compared the three different materials' behaviors in different locations where the solar irradiance can vary and result in different energy inputs and system electricity generations. The behavior of the system according to its geographical locations will be reviewed in the next section. The total embodied energy for the entire BIPV system's life cycle by materials is 7460 MJ/m^3 for single-crystalline silicon cells, 5950 MJ/m^3 for multi-crystalline silicon cells, and 2880 MJ/m^3 for amorphous silicon cells. The study showed the energy consumption for each section by its percentage, as illustrated in Table 3 [37].

The above percentages indicate that most of the energy is consumed for manufacturing, like the PV module (cell). Moreover, the amorphous silicon type is considered the most less energy consumed cell type of the three examined in this study. Nevertheless, the EBPT for the three PV modules is calculated for five different locations but only one fixed location will be recorded, the fifth-class region in Guizhou. The EPBTs for single-crystalline silicon, multi-crystalline silicon, and amorphous silicon are 7.4 years, 6.3 years and 6.1 years, respectively. The life cycle for all the three PV modules for the BIPV system is 30 years, during which they can perform more than 22 years of clean energy [37].

Table 2 Energy data analysis of BIPV and net BIPV systems

	BIPV	Net BIPV
Energy payback time (EBPT) (years)	5.5	4.8
Life time (years)	25	25
Embodied energy (MJ)	2.9	2.5
Energy saved	13.2	13.2

Table 3 The embodied energy (%) for each section of the entire life cycle of the studied materials for BIPV application

Sections/Material	Single-crystalline silicon 7460 MJ/m^3 (%)	Multi-crystalline silicon 5950 MJ/m^3 (%)	Amorphous silicon cells 2880 MJ/m^3 (%)
PV module	76	71	46
Supports	8	10	21
Inverter	4	4	4
Maintenance	7	8	14
Installation	1	1	4
Transportation	1	2	3
Recycle	3	4	8

3.2 Non-silicon-Based BIPV

Thin films technologies are an example of non-silicon-based PVs, including Cadmium telluride (CdTe) and Copper Indium Selenide (CIS). Lu and Yang [35] produced a flowchart about the processes associated with the manufacturing of thin films technologies (CdTe). At the first stage, a transparent conducting oxide (TCO-layer) is placed on a cleaned substrate glass. Then, the CdS-layer with the cadmium compound is placed on the TCO-layer by metallorganic chemical vapor depos, and grooves should be formed on the CdS-layer using a laser. After that, CdTe-layer by using atmospheric pressure closed space technique. At the final stage, the CdS or CdTe solar cell can be completed by screen printing carbon and silver contacts with the solar cell. Providing the flowchart of the processes along with the data associated with the flowchart will ease the process of quantifying the environmental impact and facilitate searches for alternatives processes that mitigate the environmental burdens of the product. An illustration of the flowchart as a cradle-to-gate boundary is described in Fig. 4 [22] (Table 4).

Several studies were conducted for the life cycle assessment and the environmental performance of BIPV non-silicon-based technologies. A review and a comparison, then, will be conducted for non-silicon-based BIPV systems. To begin with, Cadmium telluride (CdTe) solar cells were used as a façade BIPV in a past study [16]. It is a 29.3 kWp system that is estimated to generate 412.5 MWh over its entire lifetime of 25 years. The results showed that the total embodied energy needed for its life cycle is 38,750 KWhe. As a result, the EPBT is assumed to be 2.3 years. This study also compared two different types of solar cells, m-Si and CdTe. CdTe showed great environmental performance and low energy consumption and lower EPBT through its life cycle. Another LCA study, done for a BIPV system designed to be a ceramic module conducted from cradle-to-gate, did not include the disposal phase of

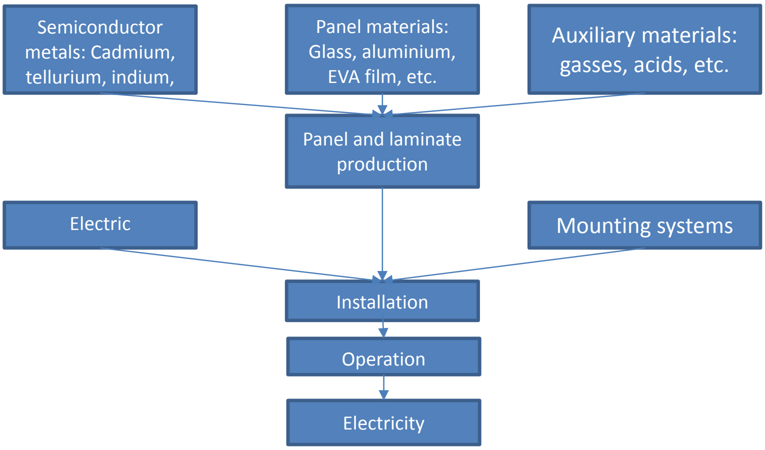

Fig. 4 Cradle-to-gate flowchart of non-Silicon based solar cell

Table 4 Type of material, EPBT, GPBT and software used for the Silicon-based BIPV

System	Material used for the cells	Energy Payback time (EPBT) (years)	Greenhouse payback time (GPBT)	Software for LCA modeling and database used
40kWp BIPV system [16]	Mono-crystalline silicon (m-Si)	6.9	N/A	N/A
22kWp BIPV system [35]	Mono-crystalline silicon (m-Si)	7.3	5.2 years	N/A
2.1 kWp BIPV system [36]	Mono-crystalline silicon (m-Si)	4.5	4 years	Simapro 7.1 and Ecoinvent V2
850 kWh/kWp/year system [14]	Poly-crystalline silicon (p-Si)	5.5	N/A	N/A
N/A [37]	Single-crystalline silicon	7.4	N/A	N/A
N/A [37]	Multi-crystalline silicon	6.3	N/A	N/A
N/A [37]	Amorphous silicon	6.1	N/A	N/A

the product. Ecoinvent v2.2 was used as the data base for the study and CML 2001 and other environmental indicators were chosen as the impact assessment methods of the BIPV ceramic module. In addition, the functional unit was set at 1 m^2 of the BIPV ceramic module. The study illustrated the vehicle types and wastes associated with producing the functional unit. The electricity needed to produce 1 m^2 of BIPV ceramic module at 56.1 kWh and the annual solar radiation in Milan is 1300 kWh/m^2 with an efficiency of 6%. Therefore, the annual electricity generation by 1 m^2 of BIPV ceramic module would be 78 kWh/m^2 annually, which results in an EPBT of 0.72 years [38]. Another study done for BIPV, which in 2004 was applied as a façade across 12 floors to a building in New York, claimed a system of capacity equal to 11.3 kWp made of BIPV Solaire. The system modeled using SimaPro V7.1, with the EPBT estimated to be 3.8 years and the lifetime to be 30 years [39]. A study of CdS or CdTe module conducted by Kato et al. [40] found that producing 1 m^2 (functional unit) PV module of CdS or CdTe can resulted in 1803 MJ, 1414 MJ, 1272 MJ of energy consumed for a 10 MW/year system, 30 MW/year system and 100 MW/year system, respectively. However, highly intensive energy is required for back cover sheet and sealant for the CdS or CdTe module. The EPBT for the systems are 1.7 years (10 MW/yr) to 1.1 years (100 MW/year), and the expected lifetime of the systems is 20 years—meaning the systems can positively impact the environment [40]. The same study compared the life cycle of CO_2 emissions, where the CdS/CdTe showed lower CO_2 emissions than silicon-based materials (poly-Si and a-Si). The life cycle CO_2 emission for poly-Si, a-Si and CdS/CdTe in a 10 MW/yr system is 19.7 g-C/kWh, 15.8 g-C/kWh and 14 g-C/kWh, respectively [40]. A study of a GaInP/GaAs, a film module, was modelled using SimaPro 7.1.8 software, a CML 2001 assessment

Table 5 Energy requirement breakdown for the processes associated with manufacturing-Si thin film technology

Process	Energy requirement (MJ/m^2)
Cell material	50
Module encapsulation material	350
Cell/module processing	400
Overhead operations and equipment manufacture	400
Module frame (aluminium)	400
Total module	1600

method, and the Ecoinvent 2.01 data base. The functional unit associated with this study is 1 kWp of power production. The author depended on illustrating the impact categories' results through the normalization of their scores, which were based on years and factors. The factor of GWP is 25, as the highest contributed process is the MOVPE reactor system [41]. Additionally, a-Si thin film technology cell module was studied to produce 1600 MJ of energy consumption per functional unit (m^2) of a-Si module and CIS cell would consume 2870 MJ/m^2. A breakdown of energy consumption for a-Si is shown in Table 5 [42].

Thin films technologies usually have lower-efficiency EPBTs than silicon technologies. As a result, the EPBT for thin films technologies differ between two and six years depends on the application if the BIPV. However, the lifetime of the system is between 20 and 30 years, which means it will still contribute positive environmental impact [42] (Table 6).

Table 6 Type of material, EPBT, GPBT and software used for the non-Silicon-based BIPV

System	Material used for the cells	Energy payback time (EPBT) (years)	Greenhouse payback time (GPBT)	Software for LCA modeling, Impact assessment method and database used
29.3 kWp system [16]	Cadmium telluride (CdTe)	2.3	N/A	EPBT
N/A [38]	BIPV Ceramic module	0.72	N/A	N/A, CML 2001, Ecoinvent v2.2
11.3 kWp [39]	BIPV Solaire system	3.8	N/A	SimaPro V7.1
10 MW/YR 30 MW/YR 100 MW/YR [40]	Cadmium telluride (CdTe)	1.1–1.7	N/A	EPBT and Major primary energy requirement (PER)
N/A [42]	A-Si and CIS	2–6	N/A	EPBT

4 Environmental Performance Based on Geographical Location

Many past studies have examined the environmental performance and the life Cycle Assessment of BIPV for the geographical place where the BIPV operated; such studies discuss the contribution of the applied BIPV system in different countries as there are multiple electricity grids and power resources. As an example, if the same system capacity is applied in two different geographical locations, the desired outcome of energy will differ mainly due the parameters that commonly affect the performance of the BIPV: temperature, solar irradiance, moisture, and dust. This was shown in a study conducted in Toronto, Montreal, and Edmonton and another one conducted in Glasgow and Sevilla where the systems have the same capacity but different energy outcomes [43, 44].

4.1 Comparison of Different BIPV Systems in Different Locations

In Hong Kong, a 22 kWp system was installed as a BIPV rooftop application. The system's module is of the mono-crystalline type and each module's peak power rates at 175 Wp. The study concluded that the total embodied energy for the entire 22 kWp system is 205,815 kWh, which includes the embodied energy of silicon purification, processing, and slicing as well as BOS, transportation, and disposal. The annual solar radiation that will be received by the system s 266,174 kWh with an average efficiency of 10.6%, meaning that the EPBT will be 7.3 years and have a lifetime of 20–30 years. In addition, the annual electricity generation of the system will be 28,154 kWh, the same value that will be saved from power station. CO_2 emissions will also be reduced. The annual CO_2 emission saved will be 28,154 kWh × 671 g CO_2eq = 18,891 kg of CO_2eq. Therefore, the total GHGE of the system is 98,834 kg CO_2eq and the GPBT will be 5.2 years. These results would be different if it applied in a different location, different application, or at a different tilt [35]. A case study done comparing two Italian cities, Milano and Palermo, applied the same technology, same tilt angle, and same orientation. However, the incident solar energy differs between Milano and Palermo, Palermo having the higher incident solar energy of the two, which means that more energy is generated in Palermo than Milano. In addition, because the incident solar in Palermo is higher, it requires less surface area for the BIPV (38.6 m^2/24 PV modules) than in Milano (46.4 m^2/29 PV modules) and both generate the same quantity of electricity. As more PV modules are required to meet the needs of electricity generation in Milano, the system will use more embodied energy and materials, resulting in more EBOT and GPBT. The EBPT and GBPT are 2.1–2.9 years and 3–3.3 years for Milano and 1.8–2.5 years and 2.5–2.8 years for Palermo. The life cycle of the system is assumed to be 20 years and the recommended technology to be used for the system is thin film [45]. In Malaysia, a case study performed for rooftop PV where the energy and electricity requirements were calculated for the production and installation of the rooftop PV system. The study divided the PV system's life cycle into three main phases: manufacturing and construction, operation, and decommissioning. In the manufacturing, construction, and decommissioning phases, there will be emissions of gases because the electricity and energy required for manufacturing and disposal will emit greenhouse gases. The average of all greenhouse emissions through the production of PV for CO_2, SO_2, and NOx are 2.757 tones/kWp, 0.015 tones/kWp and 0.007 tones/kWp, respectively. Relatedly, the total greenhouse gas emissions that will be avoided over 30 years of the PV system life cycle for CO_2, SO_2, and NOx are 20.33 tones/kWp, 0.019 tones/kWp and 0.035 tones/kWp, respectively. The electricity required for the production and installation of mono-crystalline silicon, poly-crystalline silicon, and Amorphous silicon are 5043.4 kWh/kWp, 3539.35 kWh/kWp and 3029.46 kWh/kWp, respectively. It is clear that thin film technology (a-Si) produced the least electricity and has less of an environmental impact. Furthermore, the EPBT for thin film is the least between the three materials studied (1.89–2.6 years). The range of EPBT depends on the city in which the technology is applied (in Malaysia, it would be 1.89 years if applied in Kota Kinabalu and 2.6 years if applied in Kuala Lumpur) [46]. In Shanghai, a rooftop BIPV with a system capacity of 10 kWp was installed; the material used was mono-crystalline silicon, and 54 mono-crystalline modules were implemented, each of which generates 185 Wp. The energy consumed to manufacture and produce the total BIPV system is 518940 MJ, where 87.31% of the total energy is consumed for the PV system; 12.69% of the energy consumed is for BOS equipment, and the annual saved energy will be 120021 MJ. As a result, the EPBT is calculated to be 3.1 years. In addition, the total greenhouse emissions of the system is 16376 kg. Because the BIPV is applied in place of traditional building materials, the greenhouse emissions will be reduced to 12779 kg; as indicated by the case study, the GBPT is 0.4 years [47]. Another case study, conducted in the UK for a 2.1 kWp BIPV system, was made of mono-crystalline modules and applied as a roof tile. A full LCA study was conducted to assess the environmental impact of BIPV in the UK with a functional unit of "a 2.1 kWp mono-crystalline BIPV roof tile system installed on a new build property and connected to the UK national grid with a lifetime of 25 years" [36]. Allocation for recycling was set to be the EU average where each material is recycled individually. The software used for this LCA were SimaPro 7.1, Ecoinvent V2.1 as a database, and Eco-indicator 99 as life Cycle Impact Assessment. There are 11 different environmental indicators associated with Eco-indicator 99, but the most important ones are climate change, acidification, eco-toxicity, and land use. The modeled system resulted in 83 GJ of embodied energy. The results of the eco-indicator showed that the BIPV cells contributed the most in the following seven (out of the eleven) impact categories: respiratory organics, respiratory inorganics, climate change, radiation ozone layer, acidification/eutrophication, and fossil fuels. This is mainly because cell processes and fabrication are high-energy intensive, and the entire system would generate 4500 kg CO_2eq. When reduced against the roof tile impact, it is 217 kg CO_2eq. The avoided CO_2 impact for the whole lifetime of the system, which will span 25 years, is 26,700 kgCO_2eq. As a result, the GBPT would be 4 years and the EPBT would be 4.5 years [36]. In addition to the aforementioned studies, many more have been conducted all over the world to assess the environmental performance of BIPV, some of which have been listed and summarized in the table below; BIPV in four cities in Spain [48], BIPV system in Singapore [49], BIPV system in Spain (Valladolid) [50] and BIPV in 15 cities in the US [51] (Table 7).

5 Discussion and Conclusion

BIPVs are constructed using different materials, and each type of material used to construct BIPV modules entails a different procedure of process and purification that leads to disparate environmental impacts; these differences are based on the energy consumed during the life cycle of the product when using specific module types. Many studies of different types of BIPV modules have been reviewed in this chapter. After comparing the main three modules of silicon-based BIPV, it can be noted that amorphous silicon (a-Si) is the material that consumes the least amount of energy, followed by multi-crystalline silicon (m-Si), and finally Poly-crystalline silicon (p-Si), which consumes the highest amount of energy of all the BIPV applications (as indicated in Table 3). However, the efficiency of the three materials does differ. Poly-crystalline silicon has the highest efficiency followed by multi-crystalline and then amorphous silicon. Comparing the three types of materials per m^2 of energy consumption during the life cycle show that a-Si consumes the lowest amount of energy, but that, due to its low efficiency, it will require more surface areas to match the energy production levels of m-Si and p-Si. The results can be shown in Fig. 5 [48].

But in any case, the a-Si is more environmentally friendly as it consumes less than 50% of energy compared to p-Si and m-Si [37].

Moreover, non-silicon-based BIPVs have shown to have lower CO_2 emissions than those made from silicon. At the same time, a-Si modules showed good environmental performance when enlarging the system capacity, meaning that fewer manufacturing processes and purifications are associated with larger systems and that a-Si uses the technology of thin films (as seen in Fig. 6).

Furthermore, environmental impact plays a key role in both the silicon-based and non-silicon-based modules, which do produce different results. Silicon-based modules in general consumes massive amounts of energy, which in turn increases the EPBT and the emissions associated with the modules. Thin film technology, though, consumes less energy and produces fewer emissions, and the environmental impacts will be lesser overall. In Fig. 7, the environmental impacts of IPCC GWP 100a between silicon-based modules and thin film technology modules are compared [38].

This chapter shows that both different materials and different geographical locations result in varying environmental. One explanation for this is the different electricity grids in each city, which result in different amounts of greenhouse emissions

Table 7 Summarized BIPV systems based on geographical location. (Type of material, location, application, functional unit, EPBT, GPBT and software used)

System	Material used for the cells	Location	Application	Functional unit	Energy payback time (EPBT)	Greenhouse payback time (GPBT)	Software for LCA modeling, Impact assessment method and database used
22 kWp [35]	mono-crystalline	Hong Kong	Rooftop	M^2	7.3 years	5.2 years	EPBT and GPBT
5.8 kWp and 4.8 kwp [45]	Recommended to use thin film technology	Milano and Palermo	N/A	1 PV module	2.1–2.9/1.8–2.5 years	3–3.3/2.5–2.8 years	EPBT and GPBT
2 MWp [46]	Mono-cruystalline, poly-crystalline and Amorphous silicon	Eight cities in Malaysia	rooftop	1 kWp PV	1.89–2.6 years for a-Si	N/A	EPBT
10 kwp [47]	mono-crystalline silicon	Shanghai	Rooftop	N/A	3.1 years	0.4 years	EPBT and GBPT
2.1 kwp [36]	Mono-crystalline Silicon	UK	roof tile	a 2.1 kWp mono-crystalline BIPV roof tile system installed on a new build property and connected to the UK national grid with a lifetime of 25 years	4.5 years	4 years	SimaPro 7.1, Ecoinvent V2.1, Eco-indicator 99, EPBT and GBPT

(continued)

Table 7 (continued)

System	Material used for the cells	Location	Application	Functional unit	Energy payback time (EPBT)	Greenhouse payback time (GPBT)	Software for LCA modeling, Impact assessment method and database used
200 kWp capacity [48]	Poly-crystalline	Spain (Almeria, Madrid, Pineda, Santander)	Roof-integrated	kWh	3.67, 3.76, 4.36 and 4.94 years	N/A	EPBT and Greenhouse emissions
N/A [49]	a-Si and m-Si	Singapore	Façade	81 m^2 system	2.73 years (average)	N/A	Greenhouse emissions and EPBT, Eco-invent V2.1
9.7 kWp capacity [50]	Semi-transparent glass tedlar	Spain (Valladolid)	Façade	1 m^2 of modules	4.7 years	3.8 years	SimaPro 8, Eco-invent 3.1 and ELCD, Eco-Indicator 99, EPBT
2 kWp [51]	a-Si	15 sites in United States	Rooftop	m^2 for building materials and kWh for electricity	3.39–5.52 years	N/A	Eco-balance, Human and ecological health, EPBT

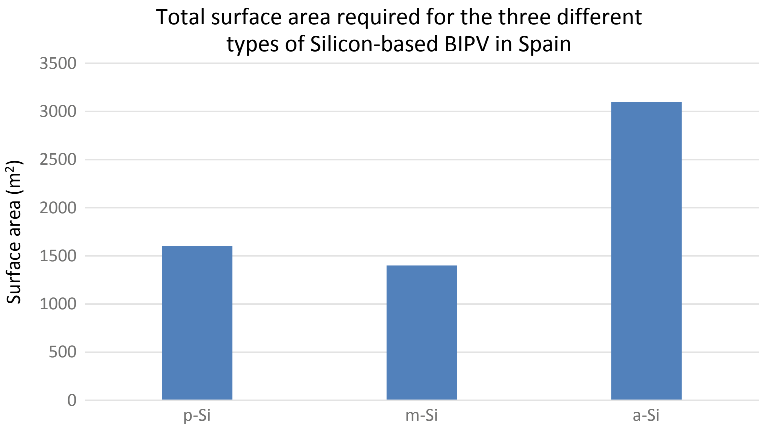

Fig. 5 Surface area comparison

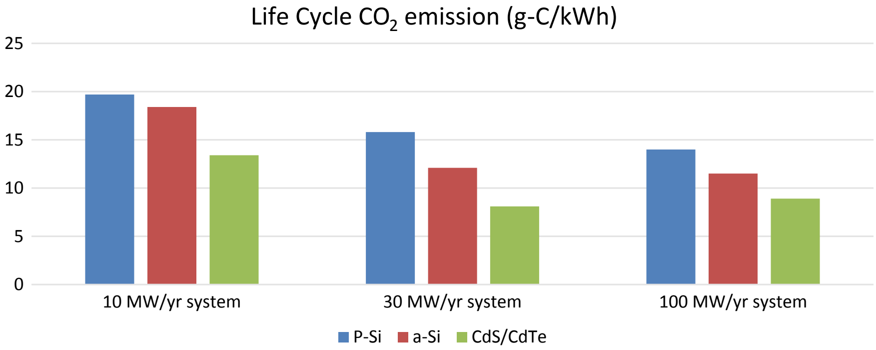

Fig. 6 CO_2 emissions of three different system capacity for three different modules

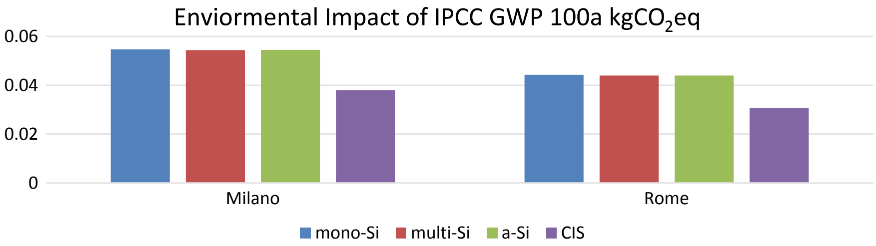

Fig. 7 IPCC GWP 100a $kgCO_2eq$ for each type of BIPV modules in two different cities which relates to the functional unit (kWh)

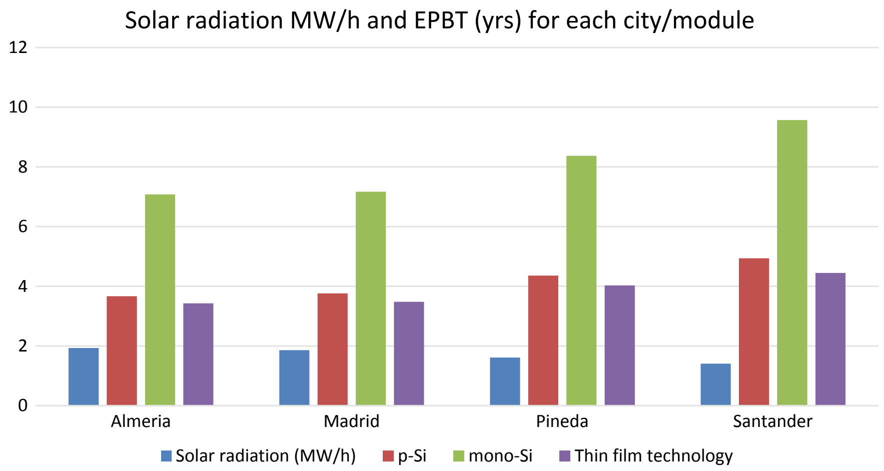

Fig. 8 Illustration for a comparison of different types of BIPV module systems and their EPBTs when applied in different geographical locations that vary by solar radiation

and different environmental impacts. However, the main reason is that the solar irradiance in each city, as shown in Fig. 8, is also different and requires more surface area of BIPV systems; that can lead to the use of more materials, more processes, and more energy to consume, which will result in either a greater or lesser environmental impact among cities [38].

It is clear that if the solar radiation is high, the surface area of the BIPV system can be optimized to the minimum. If the solar radiation is low, however, the system must be enlarged to ensure that it captures the required solar energy.

A BAPV (Building-Applied Photovoltaics) can be compared to a BIPV to see which has a better environmental impact. BAPV is a system that feeds the building with electricity but is not considered an integrated-Photovoltaics because it does not replace the building's main layers. That said, BIPV has shown to produce fewer emissions than BAPV, as BAPV requires construction of foundations because BIPV replaces the façade or rooftop—the environmental impact of which can be deducted from BIPV. In Fig. 9, it can be observed that the life cycle of BIPV system emits less CO_2, SO_2 and NOX emissions than BAPV [16].

To summarize, thin films technologies and non-silicon-based modules show better environmental performance for BIPV application, as they do not use the expansive amounts of energy used by silicon-based modules. The solar radiation of the desired system should additionally be considered; it will allow the consumer to optimize the system to the lowest capacity required by the building owner as well as determine the optimal location for applying the BIPV system. In turn, this will result in less material and energy used in the manufacturing processes.

Nevertheless, some research gaps were found when reviewing the literature:

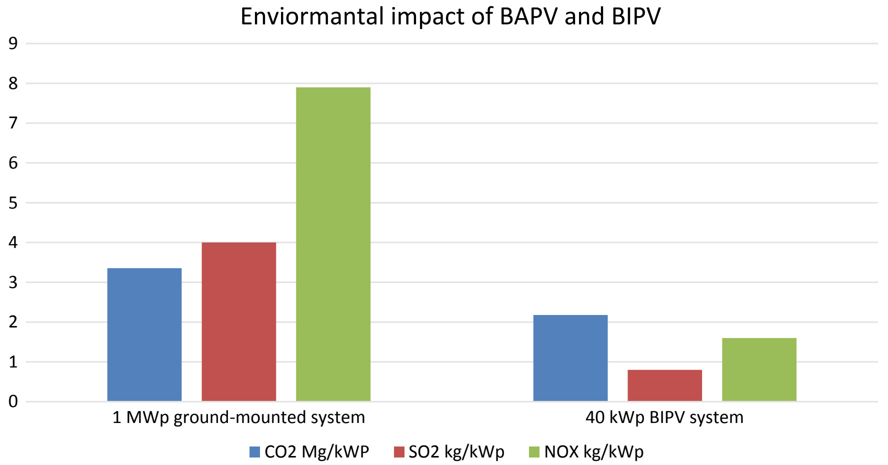

Fig. 9 Environmental impact of BAPV and BIPV per kWp (CO_2 Mg/kWp, SO_2 kg/kWp, NO_X kg/kWp)

- There is no study that dedicated the BIPV system for a full life cycle assessment study from cradle-to-grave
- It is difficult to find studies about the environmental performance of BIPV for specified types of materials and applications.

Future research should study the environmental performance of BIPV for different materials throughout the entire BIPV system, from cradle-to-grave, and this should be compared to regular rooftops or façades in terms of environmental performance and impact.

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