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Review of Tools for Sustainability Assessment of Renewable Energy Technologies for Remote Area Power Supply

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Abstract

This review discusses the tools used in the sustainability assessment of renewable energy technologies in remote area power supply systems. A comprehensive keyword search was conducted to identify widely used tools in assessing the three pillars of sustainability (economics, environmental and social). Results found that environmental life cycle assessment (ELCA), life cycle costing (LCC), social life cycle assessment (SLCA), triple bottom line (TBL) approach and eco-efficiency analysis (EEA) were commonly used worldwide to assess the environmental, economic and social implications of renewable energy technologies. Eco-efficiency analysis is recommended to be applied in the sustainability assessment of power generating technologies for remote area power supply. This tool does not only assess the economic and environmental implication of existing technologies but also assists in the implementation of improvement opportunities for a better eco-efficiency performance.

Keywords: Sustainable energy; Renewable energy; Environmental life cycle assessment, Life cycle costing; Social life cycle assessment; Triple bottom line approach

Introduction

The current energy systems have been heavily reliant on fossil fuels to run the modern economy [1]. The continuous use of fossil fuels leads to global resource scarcity and environmental and health impacts [2]. The present fossil fuel dependent economy will result into an unsustainable future [3]. Thus, to minimize detrimental effect to the biosphere and conserve resources for future generations, sustainable energy scenarios must be provided.

Implementing sustainable energy scenarios can be attained in three ways 1) utilization of clean technologies, development and deployment of renewable energy and 3) improvement of efficiency of energy transmission, distribution and consumption [4]. From a global perspective, the use of renewable energy could address future energy scarcity and avoid environmental degradation [5].

The remote area power supply (RAPS) systems in Australia have a potential to integrate renewable energy technologies (RET), as most power distribution utilities still favor fossil-fuelled generators [6,7]. The environmental benefits of RET are often neglected due to high capital cost in the integration of these technologies [8]. These energy systems are sustainable when economic and social objectives are achieved with least environmental degradation. Therefore, this paper reviews available tools for assessing the sustainability performance of RETs.

This review aims to identify the tools used that are used to assess the environmental, economic and social implications of RETs and to develop an understanding of each method. This paper also reviews a range of life cycle assessment methods that are used of sustainability assessment of RETs.

Methods

This study provides a literature review of the sustainability assessment of RET for RAPS systems. The review started with a research of keywords in databases, which include Elsevier Science Direct, ProQuest and Springer link. Keywords included for research are “renewable energy technology”, “solar photovoltaic”, “wind generator”, “hybrid energy system”, “sustainable energy”, “sustainability”, “triple bottom line” and “eco-efficiency”. The criteria used for selecting the sources were as follows:

- Scientific research for the last 10 years;
- Demonstration of environmental, economic or social implications of RET; and
- Published in English.

Forty-four sources were selected for review. These papers were sourced from a wide range of peer reviewed journals.

Categories for analyzing the sources

The reviewed articles were categorized into five tools to assess the sustainability of RETs. Several studies suggested the use of sustainability assessment tools and frameworks by the energy sector for assessing economic, environmental and social implications in the selection of power generating technologies and for decision making purposes [9-11]. The significance of several tools such as environmental life cycle assessment (ELCA), life cycle costing (LCC), social life cycle assessment (SLCA) and triple bottom line (TBL) for sustainability assessment of RET were discussed in the next section. Table 1 shows the papers reviewed on these life cycle assessment tools for assessing the sustainability performance of RET.

Sustainability Assessment Tool	Reference	Application
Environmental life cycle assessment	Al-Behadili and El-Osta [12]	1.65 MW wind generators
	Ardente et al. [13]	Wind generators in Italy
	Baharwani et al. [14]	Solar PV technologies including mono-crystalline silicon (mono-Si), multi-crystalline silicon (multi-Si) and thin-film
	Bekkelund [15]	Grid-connected and rooftop solar PV
	Chen et al. [16]	Mono-Si modules
	Demir and Taşkın [17]	Wind generators in Turkey
	Fthenakis and Kim [18]	Silicon and thin-film solar PV technologies
	Fu et al. [19]	200 Wp multi-Si modules
	Garrett and Rønde [20]	50 MW onshore wind farm
	Glassbrook et al. [21]	400 W, 2.5 kW, 5 kW and 20 kW wind generators
	Guezuraga et al. [22]	1.8 MW and 2 MW wind generators
	Hou et al. [23]	Grid-connected multi-Si modules
	Glassbrook et al. [21]	100 kW wind generator in Canada
	Kannan et al. [24]	Grid-connected solar PV technologies
	Kim et al. [25]	Cadmium telluride solar PV technology
	Menoufi et al. [26]	Building integrated concentrated PV technology
	Oebels and Pacca [27]	1.5 MW wind generators in Brazil
	Peng et al. [28]	Mono-Si, multi-Si, cadmium telluride solar PV technologies
	Petrillo et al. [29]	Various hybrid power supply system for a telecommunication station in Turkey
	Rashedi et al. [30]	50 MW horizontal axis wind generator
	Schofield [31]	Hybrid wind-diesel system
	Sevencan and Çiftcioğlu [32]	Electricity generation system for a mobile house using various alternative generating options
	Sherwani et al. [33]	Moni-Si and multi-Si solar PV technologies
	Smith et al. [34]	Hybrid diesel-solar PV-wind microgrid in Thailand
	Stoppato [35]	0.65 square meter multi-Si rooftop modules
	Sumper et al. [36]	200 kWp multi-Si rooftop modules
	Tremeac and Meunier [37]	250 W and 4.5 MW wind generators
	Tsang et al. [38]	Polymer based organic PV technology
	Uddin and Kumar [39]	Vertical and horizontal wind axis generators
	Wang and Teah [40]	Horizontal wind axis generators
	Wang and Sun [41]	1.65 MW, 3 MW, 850 kW Vestas wind generators in China
	Wu et al. [42]	Grid-connected ground-mounted solar PV technology
	Yu and Halog [43]	Grid-connected multi-Si modules
	Zhong et al. [44]	Mono-Si solar PV technology

Life cycle costing	Abbes et al. [45]	Hybrid solar PV-wind-battery system
	Akyuz et al. [46]	Diesel, hybrid solar PV-diesel-battery system and hybrid wind-diesel system
	Fan [47]	Rooftop solar PV system
	Kannan et al. [24]	2.7 kW solar PV system
	Laura and Vicente [48]	Off-shore wind farm
	Marszal et al.[49]	Renewable energy technologies for net zero energy building
	Perera et al. [50]	Standalone hybrid energy systems
	Petrillo et al. [29]	Various hybrid power supply system for a telecommunication station in Turkey
Social life cycle assessment	Atilgan and Azapagic [51]	Fossil fuel generators, geothermal, hydro and wind generators
	Traverso et al. [52]	Multi-Si solar PV modules in Germany and Italy
	Yu and Halog [43]	Grid-connected multi-Si modules
Triple bottom line approach	Atilgan and Azapagic [51]	Fossil fuel generators, geothermal, hydro and wind generators
	Li et al. [53]	Mono-Si, multi-Si and cadmium telluride solar PV technologies
	Petrillo et al. [29]	Various hybrid power supply system for a telecommunication station in Turkey
	Traverso et al. [52]	Multi-Si solar PV modules in Germany and Italy
	Yu and Halog [43]	Grid-connected multi-Si modules

Table 1: List of sustainability assessment tools applied in renewable energy technologies.

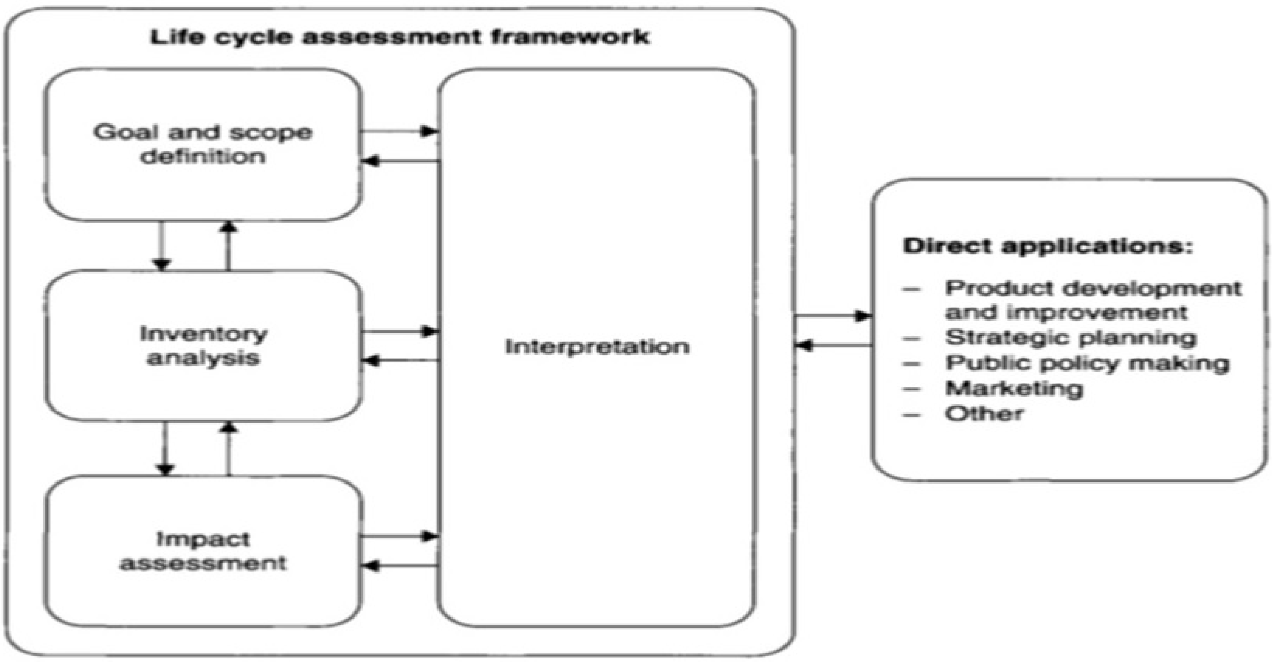

Figure 1: Framework for environmental life cycle assessment.

Sustainability assessment of renewable energy technologies

The sustainability assessment tools were used to assess the environmental, economic and social performance of various RET. The technologies evaluated in this review include solar photovoltaics (PV), wind generators and hybrid energy systems. The following section discusses the significance of each tool for sustainable energy assessment.

Environmental life cycle assessment

ELCA assesses the environmental impacts of a product or system in its entire life cycle. The widespread application of ELCA has been used in implementing environmental improvement opportunities and in comparing existing systems with improved scenario [54]. The four procedures in conducting an ELCA is shown in Figure 1.

Goal and scope definition: This stage outlines the boundaries and limitations of the analysis to meet the research goal.

Life cycle inventory: This quantifies the associated energy and material inputs and emissions of the product or system studied.

Life cycle impact assessment: This estimates the magnitude of potential environmental impacts and evaluates their importance.

Interpretation: This highlights the research findings and identifies how each inputs or processes contribute to environmental impacts.

A functional unit is used as a reference to calculate the associated inputs or output of a product or system [55]. A system boundary determines the processes included the analysis in order to define the temporal, spatial and production limits [56]. The most common system boundary used for power generating technologies is a cradle-to-grave analysis since this includes mining to material production, use and disposal stages [57].

A review of available ELCA studies on RET such as solar PV, wind generators and hybrid energy systems has been discussed below.

Review of ELCA of solar PV

The ELCA studies reviewed were conducted in developed and developing countries. Majority of these studies were performed in China due to their large solar PV production and the pressure to meet their environmental obligations [58]. Most of these ELCAs evaluated a number of environmental impacts to include the extent of environment, resource and human damage from generating solar PV electricity. Chen, Hong, Yuan and Liu [16] included sixteen impact categories consisting of climate change, terrestrial acidification, human toxicity, photochemical smog, particulate matter formation, metal depletion, terrestrial ecotoxicity, ozone depletion, freshwater ecotoxicity, marine ecotoxicity, ionising radiation, agricultural and natural land occupation, natural land transformation, fossil fuel depeltion and water depletion. Fthenakis and Kim [18], Menoufi et al. [26] and Fu et al. [19] considered evaluating various impact categories to determine the detrimental effects on ecosystems, natural resurces and human health. The energy payback time of solar PV was also assessed by some studies [24,59].

The LCIs of ELCAs were assessed based on a functional unit of 1 kWh or 1 MWh of electricity generation. A system boundary of cradle-to-gate and cradle-to-grave were used for analysis. Zhong, et al. [44] modelled and assessed various end-of-life disposal methods including landfill, recycling and incineration. Most of these studies also considered the balance of systems (BOS), which encompasses all components of a PV system other than the panels (i.e., cables, wires, inverters, batteries, frames and supporting structures) [26,42,43].

These ELCAs show that the module production accounted for 60% to 90% of primary energy consumption and greenhouse gas (GHG) emissions due to large electricity and fuel consumption during this stage[23,24,35,36,38]. The life span of solar PV technologies that range from 20 to 30 years was found to not influence the overall environmental impacts due to the negligible effect of the operation and maintenance stages [16,44].

Potential improvement strategies were applied by some studies to mitigate the environmental impact during energy intensive module production stage. Zhong et al. [44] stated that recycling of solar PV materials has environmental credits, but the benefit received is not yet fully maximised due to low recycling diversion rates. Kannan, Leong et al. [24] suggested that increasing the efficiency of module production can potentially reduce environmental impacts by 41% and replacing the support structure from aluminium to concrete can reduce these impacts by 18%.

Review of ELCA of wind generators

The studies on the environmental implications and potential policy scenarios for wind generators were from developed and developing countries. Majority of wind generator ELCAs assessed the primary energy consumption and life cycle global warming potential. Ardente et al. [13], Kabir et al. [60] and Uddin and Kumar [39] assessed acidification, eutrophication and ozone depletion, while Demir N et al. [17] and Xu L et al. [61] assessed additional impact categories including abiotic depletion, photochemical smog, human toxicity and ecotoxicities. Tremeac and Meunier [37] and Rashedi et al. [30] assessed damage categories in terms of human health, natural environment and resources.

The LCIs of these studies were calculated based on a functional unit of 1 kWh or 1 MWh of wind electricity generation [12,20,27]. Most studies have considered a cradle-to-grave system boundary to encompass the life cycle environmental implications of wind electricity generation. Some studies excluded the dismantling and disposal stages due to lack of available information on wind generator disposal pathways [27].

These ELCAs have identified that the production of wind generator components accounted more than 50% of all environmental impacts [13,60]. This finding was attributed to the large quantity of steel used to manufacture the tower (25% to 30%) followed by nacelle (15%) and foundation (10% to 15%) [22]. Although the production of steel is less energy and emission intensive than the production of copper, the large mass composition of steel (>48%) has made it an environmental hotspot [40].

Regardless of the wind generator life span, the operational stage was found to contribute the least environmental impact [12,39].

Majority of these ELCAs have suggested replacing the materials used for producing the wind generators with environmentally friendly materials to mitigate environmental impacts. Rashedi et al. [30] suggested replacing steel in the nacelle with aluminium alloy due to its lower emission intensive production. The replacement of generator blade material with fibreglass was found to reduce global warming potential by 22% and primary energy consumption by 40% [39]. Oebels and Pacca [27] have found a 6.4% reduction in environmental impacts with the replacement of steel tower by a concrete tower. An increase in recycling diversion rates can reduce the impacts due to environmental credits received from material recovery. Guezuraga et al. [22] has determined a 43% reduction in primary energy consumption and 44% in global warming potential by wind generator recycling.

Review of ELCA of hybrid energy systems

The hybrid system ELCA studies reviewed were mostly an integration of diesel generator with solar PV and wind generator. Most of these ELCAs have estimated a number of environmental impacts to determine the extent of environmental damage caused by generating electricity using hybrid systems. Schofield [31] assessed abiotic depletion, acidification, eutrophication, global warming potential, ozone depletion, photochemical depletion, while Petrillo et al. [29] evaluated the human, environment and resource damage categories. The LCIs were calculated based on a functional unit that was defined as generating electricity over an operational life of 20 to 25 years. The system boundary in all these ELCAs was a cradle-to-gate approach.

Hotspot analysis was conducted to identify the life cycle stage that causes the largest impact. Unlike solar PV and wind generators, these ELCAs show that the operational stage (diesel combustion) is responsible for the majority of environmental impacts [34]. These studies suggest that the electricity generated from RET in the hybrid system does not completely offset the environmental impacts from the combustion of fossil fuels.

Further review has been conducted to consider the economic implications of these environmentally friendly technologies.

Life cycle costing

The economic factor is fundamental in strategic decision making processes [62]. Life cycle costing (LCC) is a widely used economic tool in the analysis of revenues and costs over the entire life cycle of products or services [63]. This approach allows decision makers to be aware of significant cost parameters and assists in implementing strategies to minimise these costs [64].

LCC has been determined to be valuable in sustainability assessments as sustainable products must not only be environmentally friendly and socially equitable but also economically viable. The application of LCC in power generating technologies assists in formulating comprehensive energy policies and valuable decisions [65]. This was exemplified when NREL [66] suggested the use of LCC in providing key information for selecting power generating technologies in the US.

The LCC of RET was conducted in both developed and developing countries. Majority of these LCCs were conducted in parallel with an ELCA to determine both economic and environmental implications of RET [24,29]. The same functional unit and system boundary of these LCCs has considered the equipment acquisition, installation, operation and maintenance, dismantling and disposal stages [47,49,50].

A net present value is used for evaluating and comparing the cost-effectiveness of different RET [45,67]. The results of the studies varied due to differences in LCC objectives. The LCC of solar PVs and wind generators has shown that the capital cost constituted between 53% and 96% to total life cycle costs, while the LCC of hybrid systems has shown that the integration of RET can reduce the total life cycle cost due to reduction of fossil fuel cost.

Further research has been conducted to determine the social implications of these environmentally friendly power generating technologies.

Social life cycle assessment

The guidelines from the United Nations Environment Programme (UNEP) and Society of Environmental Toxicology and Chemistry (SETAC) are the only existing method published to conduct SLCA of a product or service [68]. This focuses on the social dimension of sustainable development in decision-making processes [69]. Although SLCA has been widely used in various studies including the food industry, waste disposal, bioenergy and construction, this has only been applied in a few RET studies.

The review of SLCA studies of RET includes the assessment of the social implications of solar PV technologies and comparative SLCA analysis of various power generating technologies worldwide. The main social indicators evaluated by the majority of these studies are wage, local employment and employment health and safety.

There is flexibility in the assessment of social implications using SLCA since no specific rule in the selection of social indicators was proposed in the UNEP and SETAC guidelines [70]. However, this could result in a lack of meaningful comparison between studies due to variability of rules followed [52]. Regardless of this limitation, SLCA can potentially be integrated with ELCA and LCC to create a Triple Bottom Line (TBL) approach for a comprehensive sustainability assessment.

Triple bottom line analysis

A TBL approach combines the three dimensions of sustainability to assess the adverse effects of economic activities on society and environment [71]. This concept was first discussed by John Elkington in 1994 when he stated that a business should consider people, planet and profit in decision-making processes [72]. In the energy sector, TBL has been used to determine the sustainability performance of power generating technologies for comparative analysis.

The TBL studies reviewed included the assessment of the sustainability performance of RETs and a comparative analysis of different technologies for on-grid and off-grid electricity generation. Majority of these studies follow ISO 14040 guidelines to conduct an environmental assessment, while the UNEP and SETAC SLCA guidelines were followed for social impact assessment. LCC and various economic tools were followed to conduct an economic assessment. The integration of the three sustainability pillars uses various approaches to conduct a sustainability assessment. A relative sustainability index (RSI) was used by Petrillo et al. [29] to determine a single value indicator, while majority of the studies used Multi-Criteria Decision Analysis (MCDA) to calculate sustainability scores [53,73].

Whilst TBL was found effective in determining the sustainability performance of power generating technologies, the lack of definitive guidelines to assess economic and social implications and to integrate the environmental, economic and social results was found to be limiting [53]. Eco-efficiency analysis (EEA) is a well-developed concept that can assist in this objective, but it does not consider the social aspect.

Eco-efficiency analysis

Eco-efficiency is a sustainability concept that aims to increase economic progress through the efficient use of natural resources. This combines two of the three components of sustainability assessment, economics and environment [74]. The eco-efficiency concept was recognised by the World Business Council or Sustainable Development (WBCSD) through a report titled *Changing Course* and defined this as, "achieved by the delivery of competitively priced goods and services that satisfy human needs and bring quality of life, while progressively reducing ecological impacts and resource intensity throughout the life cycle to a level at least within the earth's estimated carrying capacity [75,76]".

An eco-efficiency assessment tool has been developed for quantitative assessment of production values and life cycle environmental impacts of a product or system [77]. This follows the same life cycle thinking perspective of ISO 14040 guidelines to evaluate environmental impacts. An eco-efficiency assessment tool for the selection of options and alternative processes has been developed by the chemical company BASF [74]. This method evaluates economic and environmental values for the same functional unit and considers a cradle-to-grave approach [78]. Several studies have been conducted since then to determine strategic options for system optimisation, identify improvement potentials for products and processes and support communication with decision makers, researchers and consumers [79].

Previous research in the selection of power generating technologies has suggested eco-efficiency analysis to emphasize the environmental and economic implications of these technologies [80,81]. An EEA framework has been developed to integrate ELCA and LCC to assist in the implementation of improvement opportunities for the selection of environmentally friendly and economically viable power generating technologies for the RAPS systems in Australia.

Conclusion

This review discusses various sustainability tools that can be used in the identification of renewable energy technologies in remote area power supply. Various sustainability tools including environmental life cycle assessment (ELCA), life cycle costing (LCC), social life cycle assessment (SLCA), triple bottom line (TBL) approach and eco-efficiency analysis (EEA) can be used to understand the environmental, economic and social implications of these technologies. Whilst the individual tools can be beneficial in their own ways, their applicability will be defined by the objective and goal of the study. For remote area power supply, EEA approach was found to be effective in selecting environmentally friendly technologies with the least environmental expense. Due to the rapid expansion of remote mining and agricultural activities in Australia, the application of EEA could be beneficial for energy planners and decision makers for achieving sustainable energy goals.

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