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

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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 that are used to assess the environmental, economic and social impacts 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.

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

| Citation | Description |
|----------|-------------|
| 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

| Citation | Description |
|----------|-------------|
| 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

| Citation | Description |
|----------|-------------|
| 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 for 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 ELCA 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 depletion 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 resources and human health. The energy payback time of solar PV was also assessed by some studies [24,59].

The LCIs of ELCA 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 ELCA 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. Tremac 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 ELCA 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. Guerzuraga 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 ELCA's 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 ELCA's 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 ELCA's 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 PV's 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 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.

References

1. Tester J, Drake E, Driscoll M, Golay M, Peters W (2005) Sustainable energy - the engine of sustainable development: Sustainable energy choosing among options. The MIT Press, England.
2. Boyle G, Everett B, Ramage J (2003) Introductory overview: Energy systems and sustainability. Oxford University Press, United Kingdom.
3. Pardo Martínez CI (2015) Energy and sustainable development in cities: a case study of Bogotá. Energy 92: 612-621.
4. Golusin M, Dodis S, Popov S (2013) energy and sustainable development: Sustainable energy management. Academic Press, Boston.
5. Kaygusuz K, Kaygusuz A (2002) Renewable energy and sustainable development in Turkey. Renewable Energy 25: 431-453.
6. ARENA (2014) Australia's off-grid clean energy market research paper.
7. Evans, Peck (2011) Assessment of the potential for renewable energy projects and systems in the Mid West.
8. McHenry MP (2009) Why are remote Western Australians installing renewable energy technologies in stand-alone power supply systems? Renewable Energy 34: 1252-1256.
9. Allan G, Eromenko I, Gilmartin M, Kockar I, McGregor P (2015) The economics of distributed energy generation: a literature review. Renew Sust Energ Rev 42: 543-556.
10. Holtmeyer ML, Wang S, Axelbaum RL (2013) Considerations for decision-making on distributed power generation in rural areas. Energy Policy 63: 708-715.
11. Väisänen S, Mikkilä M, Havukainen J, Sokka L, Luoranen M, et al. (2016) Using a multi-method approach for decision-making about a sustainable local distributed energy system: a case study from Finland. J Clean Prod 107: 1330-1338.
12. Al-Beahadli SH, El-Osta WB (2015) Life cycle assessment of Dernah (Libya) wind farm. Renewable Energy 83: 1227-1233.
13. Ardente F, Beccali M, Cellura M, Lo Bruno V (2008) Energy performances and life cycle assessment of an Italian wind farm. Renew Sust Energ Rev 12: 200-217.
14. Baharwani V, Meena N, Dubey A, Sharma D, Brighu U, et al. (2014) Life cycle inventory and assessment of different solar photovoltaic systems.
15. Bekkelund K (2013) Life cycle assessment of thin solar films. Norwegian University of Science and Technology, Norway.
16. Chen W, Hong J, Yuan X, Liu J (2016) Environmental impact assessment of monocrystalline silicon solar photovoltaic cell production: a case study in China. J Clean Prod 112: 1025-1032.
17. Demir N, Taşkın A (2013) Life cycle assessment of wind turbines in Çanakkale. J Clean Prod 54: 253-263.
18. Fthenakis VM, Kim HC (2011) Photovoltaics: life-cycle analyses. Solar Energy 85: 1609-1628.
19. Fu Y, Liu X, Yuan Z (2015) Life-cycle assessment of multi-crystalline photovoltaic (PV) systems in China. J Clean Prod 86: 180-190.
20. Garrett P, Ronde K (2013) Life cycle assessment of wind power: comprehensive results from a state-of-the-art approach. The International Journal of Life Cycle Assessment 18: 37-48.
21. Glassbrook KA, Carr AH, Drones ML, Oakley TR, Kamens RM, et al. (2014) Life cycle assessment and feasibility study of small wind power in Thailand. Energy for Sustainable Development 22: 66-73.
22. Guezuraga B, Zauerer R, Polz W (2012) Life cycle assessment of two different 2 MW class wind turbines. Renewable Energy 37: 37-44.
23. Hou G, Sun H, Jiang Z, Pan Z, Wang Y, et al. (2016) Life cycle assessment of grid-connected photovoltaic power generation from crystalline silicon solar modules in China. Applied Energy 164: 882-890.
24. Kannan R, Leong KG, Osman R, Ho HK, Tao CP (2006) Life cycle assessment study of solar PV systems: An example of a 2.7 kWp distributed solar PV system in Singapore. Solar Energy 80: 555-563.
25. Kim H, Cha K, Fthenakis VM, Sinha P, Hur T (2014) Life cycle assessment of cadmium telluride photovoltaic (CdTe PV) systems. Solar Energy 103: 78-88.
26. Menoufi K, Chemisiana D, Rosell JJ (2013) Life cycle assessment of a building integrated concentrated photovoltaic scheme. Applied Energy 111: 505-514.
27. Oebels KB, Pacca S (2013) Life cycle assessment of an onshore wind farm located at the northeastern coast of Brazil. Renewable Energy 53: 60-70.
28. Peng J, Lu L, Yang H (2013) Review on life cycle assessment of energy payback and greenhouse gas emission of solar photovoltaic systems. Renew Sust Energ Rev 19: 255-274.
29. Petrohillos G, De Felice F, Ianneli E, Autorino C, Minutillo M, et al. (2016) Life cycle assessment (LCA) and life cycle cost (LCC) analysis model for a stand-alone hybrid renewable energy system. Renewable Energy 95: 337-355.

30. Rashidi A, Sridhar I, Tseng KJ (2013) Life cycle assessment of 50MW wind farms and strategies for impact reduction. Renew Sust Energ Rev 21: 89-101.

31. Schoefield J (2011) Comparing the environmental impacts of diesel generated electricity with hybrid diesel-wind electricity for off grid first nation communities in Ontario incorporating a life cycle approach. Ryerson University, Toronto, Canada.

32. Sevencan S, Çiftcioglu GA (2013) Life cycle assessment of power generation alternatives for a stand-alone mobile house. Int J Hydrg Energy 38: 14569-14579.

33. Sherwani AF, Usmani JA, Varun (2010) Life cycle assessment of solar PV based electricity generation systems: a review. Renew Sust Energ Rev 14: 540-544.

34. Smith C, Burrows J, Scheier E, Young A, Smith J, et al. (2015) Comparative life cycle assessment of a Thai Island's diesel/ PV/wind hybrid microgrid. Renewable Energy 80: 85-100.

35. Stoppato A (2008) Life cycle assessment of photovoltaic electricity generation. Energy. 33: 224-232.

36. Sumper A, Robledo-García M, Villafáfila-Robles R, Bergas-Jané J, Andrés-Peiró J (2011) Life cycle assessment of a photovoltaic system in Catalonia (Spain). Renew Sust Energ Rev 15: 3888-3896.

37. Tremeac B, Meunier F (2009) Life cycle analysis of 4.5 MW and 250 W wind turbines. Renew Sust Energ Rev 13: 2104-2110.

38. Tsang MP, Sonnemann GW, Bassani DM (2016) Life-cycle assessment of cradle-to-grave opportunities and environmental impacts of organic photovoltaic solar panels compared to conventional technologies. Sol Energy Mater Sol Cells 46: 37-48.

39. Uddin MS, Kumar S (2014) Energy, emissions and environmental impact analysis of wind turbine using life cycle assessment technique. J Clean Prod 69: 153-164.

40. Wang WC, Teah HY (2017) Life cycle assessment of small-scale horizontal axis wind turbines in Taiwan. J Clean Prod 141: 492-501.

41. Wang Y, Sun T (2012) Life cycle assessment of CO2 emissions from wind power plants: Methodology and case studies. Renewable Energy 43: 30-36.

42. Wu P, Ma X, Ji J, Ma Y (2017) Review on life cycle assessment of energy payback of solar photovoltaic systems and a case study. Energy Procedia 105: 68-74.

43. Yu M, Halog A (2015) Solar photovoltaic development in Australia—A life cycle sustainability assessment study. Sustainability 7: 1213-1247.

44. Zhong ZW, Song B, Loh PE (2011) LCAs of a polycrystalline photovoltaic module and a wind turbine. Renewable Energy 36: 2227-2237.

45. Abbas D, Martinez A, Champenois G (2014) Life cycle cost, embodied energy and loss of power supply probability for the optimal design of hybrid power systems. Mathematics and Computers in Simulation 98: 46-62.

46. Akyuz E, Oktay Z, Dincer I (2011) Energetic, environmental and economic aspects of a hybrid renewable energy system: a case study. International Journal of Low-Carbon Technologies 6: 44-54.

47. Fan J (2014) Life cycle assessment and life cycle cost of photovoltaic panels on Lake Street parking garage. Colorado State University, Colorado, USA, Ann Arbor.

48. Laura CS, Vicente DC (2014) Life-cycle cost analysis of floating offshore wind farms. Renewable Energy 66: 41-48.

49. Marsal AJ, Heiselberg P, Lund Jensen R, Nørgaard J (2012) On-site or off-site renewable energy supply options? Life cycle cost analysis of a net zero energy building in Denmark. Renewable Energy 44: 154-165.

50. Perera ATD, Attalage RA, Perera KKCK, Dassanayake VPC (2013) Designing standalone hybrid energy systems minimizing initial investment, life cycle cost and pollutant emission. Energy 54: 220-230.

51. Atlahan B, Azapagic A (2016) An integrated life cycle sustainability assessment of electricity generation in Turkey. Energy Policy 93: 168-186.

52. Traverso M, Asdrubali F, Francia A, Finkbeiner M (2012) Towards life cycle sustainability assessment: an implementation to photovoltaic modules. The International Journal of Life Cycle Assessment 17: 1068-1079.

53. Li T, Roskilly AP, Wang Y (2017) Life cycle sustainability assessment of grid-connected photovoltaic power generation: A case study of Northeast England. Applied Energy.

54. https://www.iso.org/standard/38498.html.

55. Heijungs R, Guinee J (2012) An overview of the life cycle assessment method - past, present, and future. Life cycle assessment: A guide for environmentally sustainable products. Scrivener Publishing LLC, Massachusetts.

56. http://www.fulefromwaste.eu/download/D6_1_09302014.pdf.

57. Klopfier W (2014) Background and future prospects in life cycle assessment. Springer, Netherlands.

58. Puttasswamy N, Ali MS (2015) How did China become the largest solar PV manufacturing country?

59. Sharma R, Tiwari GN (2013) Life cycle assessment of stand-alone photovoltaic (SAPV) system under on-field conditions of New Delhi, India. Energy Policy 63: 272-282.

60. Kabir MR, Rooke R, Dassanayake GDM, Fleck BA (2012) Comparative life cycle energy, emission, and economic analysis of 100 kW nameplate wind power generation. Renewable Energy 37: 133-141.

61. Xu L, Pang M, Zhang L, Poganietz WR, Marathe SD (2017) Life cycle assessment of onshore wind power plants in China. Resources, Conservation and Recycling 132: 361-368.

62. Wubbenhorst KL (1996) Life cycle cost for construction projects. Long Range Planning 19: 87-97.

63. Vlastari J (2014) Using life cycle costing for product management. Management 19: 205-218.

64. Ally J, Pryor T (2016) Life cycle costing of diesel, natural gas, hybrid and hydrogen fuel cell bus systems: An Australian case study. Energy Policy 94: 285-294.

65. Soni V, Dash AP, Singh SP, Banwet DK (2014) Life cycle costing analysis of energy options: in search of better decisions towards sustainability in Indian power & energy sector. Global Journal of Management and Business Research 14: 42-54.

66. NREL (2013) Power generation technology comparison from a life cycle perspective.

67. Palanisamy TA (2013) Wind farm life cycle cost analysis. Texas A&M University-Kingsville, Texas, USA.

68. http://www.unep.fr/shared/publications/pdf/dtix1164xpa-guidelines_slca.pdf.

69. Finkbeiner M, Schau EM, Lehmann A, Traverso M (2010) Towards life cycle sustainability assessment. Sustainability 2: 3309-3322.

70. Schlör H, Zapp P, Marx J, Schreiber A, Hake JF (2015) Non-renewable resources for the Energiewende – a social life cycle analysis. Energy Procedia 75: 2879-2883.

71. Orgun K, Flanders CD, Buys I (2015) Renewable energy distribution in public spaces: analyzing the case of Ballast Point Park in Sydney, using a triple bottom line approach. Journal of Landscape Architecture 10: 18-31.

72. Jackson A, Boswell K, Davis D (2011) Sustainability and triple bottom line perspectives. Accounting and the Public Interest 13: 105-131.

73. Bewley K, Schneider T (2013) Triple bottom line accounting and energy-efficiency retrofits in the social-housing sector: A case study. Accounting and the Public Interest 13: 105-131.

74. Eberendf JD (2005) Eco-efficiency: philosophy, theory and tools. Journal of Industrial Ecology 9: 6-8.

75. Cope DR (1993) Eco-efficiency - changing course: a global business perspective. Nature 362: 124.
76. Verfaillie H, Bidwell R (2000) Measuring eco-efficiency: a guide to reporting company performance.
77. https://www.iso.org/standard/43262.html
78. Kicherer A, Schaltegger S, Tschochohei H, Pozo BF (2007) Eco-efficiency. The International Journal of Life Cycle Assessment 12: 537-543.
79. Saling P, Kicherer A, Dittrich-krämer B, Wittlinger R, Zombik W, et al. (2002) Eco-efficiency analysis by BASF: The method. The International Journal of Life Cycle Assessment 7: 203-218.
80. Arabi B, Munisamy S, Emrouznejad A, Shadman F (2014) Power industry restructuring and eco-efficiency changes: a new slacks-based model in Malmquist–Luenberger Index measurement. Energy Policy 68: 132-145.
81. Burnett RD, Hansen DR (2008) Ecoefficiency: Defining a role for environmental cost management. Accounting, Organizations and Society 33: 551-581.