E3S Web of Conferences **545**, 01001 (2024) https://doi.org/10.1051/e3sconf/202454501001
ICSREE 2024

Life cycle environmental assessment of hybrid renewable energy system

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Abstract. Life cycle environmental assessment is essential in assessing system performance for sustainable ecosystem. This study presented the ecological effect of installation of renewable energy systems in site Doomadgee of Far North Queensland. The aim is to determine the ecological footprint of a renewable system in sustaining the ecology. The findings of the study indicate wind turbines with the highest impacts on climate change ($1.45E^{+11}$ kg CO_2 eq), acidification potential ($3.82E^{+08}$ mol H^+ eq), eutrophication potential ($6.56E^{+04}$ kg P eq). PEM electrolyser has the highest impact in the Ozone depletion category (24.87 kg CFC11 eq). The lowest impact arises because of PEM electrolyser in all categories except ozone depletion where the lowest contribution (0.072 kg CFC11 eq) comes from a wind turbine.

1 Introduction

Weather changing resulted from the burning of fossil fuels has become a major concern for the globe. Shift of fossil fuel-based energy systems to eco-friendly resources is required to combat climate change. Solar and wind as a clean resource can play important roles in decarbonising energy systems. Energy generation by renewable resources is known as eco-friendly technology. However, they induce some environmental burdens during manufacturing, installation, and maintenance although they do not emit greenhouse gas (GHG) directly during operation. Many works have already dealt with life cycle environmental assessment (LCEA) of renewable technologies [1–4]. Tahara et al. (1997) reported carbon payback time for future renewable energy systems and compared with fossil fuel (coal, oil, LNG) power generation to determine the carbon reduction potency of renewable sources [5].

The lifetime carbon emissions from coal, solar photovoltaic (PV), and solar thermal power generation are calculated by Kreith et al. (1990) to examine the carbon emission quantity and hence, execute the strength of green energy systems [6]. Schleisner (2000) assessed the energy payback time and emissions associated with the production and manufacturing of materials for an offshore wind farm including the impact on land use [7].

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Tripanagnostopoulos et al. (2005) studied LCEA for PV/T and PV to assess the energy and carbon payback time [8]. Surplus energy from PV can replace fossil fuel in mobility with the prospectus of significantly reducing carbon emissions [9].

A LCEA approach to wind and coal power generation showed, that despite the requirement of large land areas wind power generation resulted in very few avian deaths and a significantly lower amount of carbon emissions compared to coal power generation [10]. The power produced by biomass and wind, instead of coal, can remarkably minimise global warming and fossil fuel consumption in Denmark [11]. Hydrogen-based power generation for residential use can minimise NOx and SO_2 emissions by 95% and 93% respectively compared to lignite-based power generation [12]. Different renewable energies combined with hydrogen energy carriers can address both the energy and environmental issues of any local community. A study has shown that hydrogen-battery storage-based systems including renewables and diesel gensets can reduce ecological impact significantly compared to diesel-only system [13]. Another study regarding wind-hydrogen-based system has provided that this system has ecological benefits over the diesel-based scenario [14]. A Norwegian island-based study has shown that hybridisation of solar PV, wind, and diesel genset with hydrogen storage can lessen GHG emission compared to diesel only system (Bironas et al., 2022). There are some LCA studies for individual components, such as solar PV [15] wind turbine [16–18], fuel cell [19], electrolyser [20–22], hydrogen storage [23], heat pump [24–26], battery [27].

Few studies investigated the ecological performance of hybrid renewable systems constituting solar PV, wind turbine (WT), Proton exchange membrane fuel cell (PEMFC), Proton exchange membrane electrolyser (PEMEL), and hydrogen storage. According to the Written Declaration of the European Parliament [28], where it is emphasised that "global warming and costs of fossil fuels are increasing and having regard to the debate launched by the European Parliament and the Commission on the future of energy policy and climate change, a post-fossil fuel and post-nuclear energy vision should be the next important project of the European Union". Minimising global warming, introducing renewable energies, and establishing hydrogen fuel cell technology are the key factors of the present world for transition to a net zero emission energy system. Similarly, the hybrid renewable energy system including hydrogen energy carriers could contribute the sustainable environmental target of Australia and simultaneously that could give energy independence continuous supply.

This study aims to quantify the environmental impact of the proposed hybrid system including solar, wind, and hydrogen energies on the FNQ's ecological system. A range of indicators such as climate change, eutrophication, ozone layer depletion, acidification, etc will be evaluated through LCEA. The assessment approach has provided extensive coverage on a whole system level, instead of just product level. This study represents the first comprehensive life cycle environmental assessment of an off-grid hybrid renewable energy system for FNQ. The findings will be valuable for policymakers to establish a hybrid renewable energy system in FNQ.

2 Materials and methods

In this study, LCEA is implemented as a methodological frame for estimating the ecological gains of hybrid energy systems. OpenLCA 1.11.0 is used to conduct LCA. A fully renewable hybrid energy system constituting solar photovoltaic, wind turbine, PEM fuel cell, PEM electrolyser, and hydrogen storage is considered to proceed LCA. HOMER software is used for getting the capacity of each component and electrical output. The Doomadgee load profile is collected from Ergon Energy retail to run the simulation. The electrical output of the system is a functional unit in this study.

The system boundary in this study is the whole life span of each component of the system; from the materials extract phase continuing through fabrication, installation, operation, and maintenance to recycling or landfilling of wastages. Inventory analysis is based on collected data from literature or existing databases. All the material and energy input, waste output, including emissions of all activities within the system boundary are quantified. Table 1 represents data regarding materials input for manufacturing of solar PV and wind turbine of the system as well as Table 2 represents materials information of PEM electrolyser, PEM fuel cell, and hydrogen storage.

Table 1. Material information for solar PV and wind turbine.

Material (Solar PV including inverter)	Amount	Material (Wind turbine)	Amount
Monocrystalline silicon block	0.792 kg	Low alloy steel	11.60 t
Ethylene vinyl acetate copolymer	2.47 kg	High alloy steel	10.44 t
Tin (99.92%)	0.13 kg	Cast iron	60.32 t
Copper	0.029 kg	Aluminium	0.232 t
Polyethylene terephthalate-bottle (PET)	0.95 kg	Copper	0.116 t
Aluminium part	2.43 kg	Glass fiber	40.60 t
Glass cullet	16.94 kg	Polymer	2.32 t
Copper fittings	0.25 kg	Glass fiber reinforced plastic	1.16 t
Silica	0.3123 kg	Epoxy resin	15.08 t
Energy, from gas, natural	52.18 MWh	Paint	1.16 t
Aluminium alloy	0.55 gm	Balsa wood	1.16 t
Copper	0.16 gm	Adhesive	3.48 t
Low alloyed steel	011 gm	Lubricant	0.116 t
Corrugated board box	0.71 gm	Low alloy steel	11.43 t
Capacitor, electrolytic	0.043 gm	High alloy steel	38.10 t
Capacitor, film	0.058 gm	Cast iron	67.31 t
Capacitor, cmc	0.0039 gm	Aluminium	1.27 t
Resistors	0.00081gm	Copper	10.16 t
Acrylonitrile abs polymer	0.12 gm	Electronics	0.127 t
Transformer	0.25 gm	Acrylic varnish	1.94 t
Polycarbonate	0.0055 gm	Steel	279.43 t
Polyethelene	0.0011 gm	Steel sheet	279.43 t
Polyvinyl chloride	0.00016 gm	Concrete Steel forging part Energy for installation or dismantling (diesel burning in construction machine)	3211.15 t 116.46 t 4119.45 MJ

Table 2. Materials information for PEM electrolyser and PEM fuel cell.

Material (PEM electrolyser)	Amount	Material (PEM fuel cell)	Amount
Steel	16.53 kg	Graphite	4.50 kg
Steel sheet	6.26 kg	Polyvinylidene chloride	1.10 kg
Stainless steel	17.88 kg	Aluminium	0.30 kg
Stainless steel sheet	0.42 kg	Chromium steel	0.10 kg
Aluminium	5.27 kg	Glass fiber	0.10 kg
Aluminium sheet	0.032 kg	Perfluoro sulphonic acid	0.07 kg
Iridium	0.0007 kg	Carbon black	0.0008 kg
Nafion	0.016 kg	Platinum	0.00075 kg
Platinum	0.0002 kg	Steel	3.70 kg

Titanium (transition metal)	0.475 kg	Polyethylene, high density	1.75 kg
Glass	0.013 kg	Chromium steel	1.10 kg
Brass	0.32 kg	Cast iron	0.80 kg
Polypropelene	0.194 kg	Aluminium	0.75 kg
Polyethelene	0.032 kg	Polyethylene	0.25 kg
Thermoplastic	1.74 kg	Electricity	16.90 kg
Silica	0.654 kg		
Peek	0.223 kg		
Polyamide	0.0475 kg		
Steel, electrogalvanised	0.0284 kg		
PFTE	0.00928 kg		
EPDM	0.00358 kg		
PVDF	0.006 kg		
PVC	0.1278 kg		
Cast iron	0.076 kg		
Ceramic	0.627 kg		

3 Results and interpretation

The outcomes in different ecological impact classes namely climate change, acidification, eutrophication, and ozone depletion, for the assessment of hybrid energy system, are analysed in this section.

3.1 Climate change

Climate change is caused by global warming, which is resulted from the greenhouse gases (i.e., CO_2, CH_4, N_2O, and VOC among others, but mostly CO_2) emission. Climate change is a serious condition in making decision about the power system. The major contribution to climate change is from wind turbines ($1.45E^{+11}$ kg CO_2 eq), followed by solar PV ($8.21E^{+10}$ kg CO_2 eq), PEM fuel cell (3.83E+10 kg CO_2 eq), and PEM electrolyser ($3.71E^{+09}$ kg CO_2 eq). The outcomes indicate that the indirect emission is linked with the activities of whole life-span of the system, where major contribution to climate change come from wind turbine.

3.2 Acidification potential

Acidification potential is occurred by emitting pollutants such as SO_2, HCl, NH_3, and HF gases to atmosphere. A wind turbine is the major contributor with a value $3.82E^{+08}$ mol H^+ eq followed by solar PV ($2.09E^{+08}$ mol H^+ eq), Pem electrolyser ($9.64E^{+06}$ mol H^+ eq), and PEM fuel cell ($1.01E^{+08}$ mol H^+ eq). The renewable system is also responsible for acidification. This is actually caused by fossil-based subcomponents.

3.3 Eutrophication

Eutrophication is the pollution of water bodies through oxygen depletion, caused by the accumulation of huge minerals and nutrients such as N_2, NOx, NH_4^+, $PO4^{3-}$, and P. This impact is largely due to wind turbine and solar PV with the values of $6.56E^{+04}$ kg P eq and $4.31E^{+04}$ kg P eq respectively. PEM electrolyser ($2.45E^{+03}$ kg P eq) and PEM fuel cell ($1.72E^{+04}$ kg P eq) have also contribution. Therefore, it can be said that wind power in a hybrid system is the most responsible component to release minerals and nutrients. Minerals and nutrients tend to interact water bodies, resulting excessive aquatic plant and algal growth. Algal growth may deplete dissolved oxygen, which is very harmful for aquatic ecosystem.

3.4 Ozon depletion

Ozon-layer depletion potential (ODP) impact category, caused by various chlorofuoro carbons and halogenated compounds is one of the key factors for hybrid energy system decision. Energy related activities during the whole life-time of the system may emit these dangerous gases. These gases can destroy ozon layer quickly, and eventually may cause cancer, cataracts, and worsened immune system. The result is found for PEM electrolyser, PEM fuel cell, Solar PV, and wind turbine with the values of respective 24.86915282 kg CFC11 eq, 5.316422 kg CFC11 eq, $9.49E^{-01}$ kg CFC11 eq, and 0.072054502 kg CFC11 eq. PEM electrolyser is found worst in ozon depleting category. Manufacturing of the component is mainly responsible for emitting ozon destroying gases.

4 Conclusion

This study has conducted thorough investigation regarding the ecological effect of installation of renewable energy systems in the Doomadgee region of Far North Queensland. Selected impact classes are scrutinised, and renewable technologies have negative impacts on ecology although they are referred as clean energy sources. This is caused by fossil based various process including component manufacturing stage of the system. Nonetheless, exploring renewable resources in the case study region to lower the consumption of fossil fuels, is significant for sustainable ecosystem. Renewables can offer minimum impacts compared to conventional scenario path.

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