Solar Energy 142 (2017) 159–170

Contents lists available at ScienceDirect

Solar Energy

journal homepage: www.elsevier.com/locate/solener

Economic analysis and environmental impact of flat plate roof mounted solar energy systems

Jee Joe Michael [a,*], Iniyan Selvarasan [b]

[a] Department of Mechanical Engineering, Veltech Dr. RR & Dr. SR University, Chennai 600 062, India
[b] Institute for Energy Studies, Department of Mechanical Engineering, Anna University, Chennai 600 025, India

ARTICLE INFO

Article history:
Received 20 June 2016
Received in revised form 2 December 2016
Accepted 9 December 2016

Keywords:
Embodied energy
CO_2 emission
Economic analysis
Solar energy
Photovoltaic thermal
Solar water heater

ABSTRACT

The flat plate solar water heating system and solar photovoltaic (PV) system are two mature technologies available in the commercial market, which can decrease the residential energy requirement substantially. Several research organizations are working on solar PV/T system to make it competitive to solar thermal system and solar PV system. Innovative designs over the decades have improved the performance of the solar PV/T collector significantly. However, the choice of material-of-construction play a vital role in reducing the mass, cost, embodied energy and embodied CO_2 emissions of the solar PV/T collector. In this paper, a solar PV/T based water heating system was compared with a solar PV system and a flat plate solar water heating (SWH) system based on economic evaluation and environmental assessment. Results obtained show that due to the higher overall efficiency, the solar PV/T system has better benefit-to-ratio compared to solar PV system, while being competitive to solar thermal system. Also, it makes the best use of the available domestic roof-space, minimizes quantity of construction materials and payback period. Further, the embodied energy and embodied CO_2 emission of the PV/T collector is less than the other two solar energy systems combined.

1. Introduction

The prime importance of renewable energy technologies is to provide an alternate competitive solution to conventional energy technologies and to reduce the carbon footprint. The solar photovoltaic system and solar water heating system installed in vacant building roofs as an energy resource, economic asset and environmental value have the potential to offset the energy needs and reduce the carbon footprint by a significant amount, while making considerable electricity savings. The solar PV/T technology satisfies both the electricity and hot water requirement in a limited shadow free roof space of residential consumers. The success of the PV/T system depends on the economic viability, social acceptance and environmental sustainability. There are numerous studies on the environmental and economic aspects of solar energy systems namely solar PV system and solar thermal (SWH) system. Some of the relevant studies are included as follows.

A hybrid PV-wind-battery system was designed as an economic and environmental advantage by considering the life cycle cost and embodied energy (Abbes et al., 2014). An overview of the social and environmental impacts of PV technologies are discussed by Dubey et al. (2013), and analysed for a 1.2 kW_p PV system in different climatic conditions of India (Nawaz and Tiwari, 2006). Also, the future CO_2 emissions were projected based on twenty life cycle assessment (LCA) studies for carbon capture, storage and emission reduction rates of solar PV technologies (Mansouri et al., 2013). The majority of the embodied greenhouse gas (GHG) emission was in the PV modules (Rogers et al., 2015), hence three PV modules from different manufacturers were compared for greenhouse potential, economics based on Life Cycle Sustainability Assessment (LCSA) studies (Traverso et al., 2012), embodied payback period (Wilson and Young, 1996), energy payback period and CO_2 emission (Hoque et al., 2014). The solar PV system production emission intensity varied between 1 gCO_2eq./kW h and 218 gCO_2eq./kW h using renewable energy and fossil fuel energy respectively (Nugent and Sovacool, 2014). The Energy Payback Time (EPBT) of mC-Silicon PV systems range from 1.7 to 2.7 years with GHG emission ranging from 29 to 45 gCO_2eq./kW h (Peng et al., 2013). The environmental impact of PV system (Lamnatou et al., 2014), proved that building integrated PV system had superior environmental performance (Pearce and Lau, 2002) and higher economic viability compared to larger PV systems (Jung and Tyner, 2014). The environmental impacts of solar PV system can be reduced by better efficient manufacturing process and higher conversion efficiency of the PV cell and convertors (Marimuthu and

* Corresponding author.
E-mail address: jeemjoel@gmail.com (J.J. Michael).

http://dx.doi.org/10.1016/j.solener.2016.12.019
0038-092X/

Nomenclature

AC	Alternating Current
B/C	Benefit to Cost ratio
BOS	Balance of System
CER	Certified Emission Reduction
CHP	Combined Heat and Power
CO_2	Carbon Dioxide
CPBT	Carbon Pay Back Time
CPVC	Chlorinated Poly Vinyl Fluoride
d	discount rate
DC	Direct Current
DPP	Discounted Payback Period
E	energy (J)
EPBT	Energy Pay Back Time
EPDM	Ethylene Propylene Diene Monomer
EVA	Ethylene Vinyl Acetate
EYF	Energy Yield Factor
FPC	Flat Plate Collector
GHG	Green House Gas
I	Current (ampere)
IRR	Internal Rate of Return
LCA	Life Cycle Analysis
LCIA	Life Cycle Impact Assessment
LCOE	Levelized Cost of Energy
LCSA	Life Cycle Sustainability Assessment
LPD	Litres Per Day
mC	Mono-Crystalline
NPV	Net Present Value
PUF	Poly-Urethane Foam
PV	Photovoltaic
PVF	Poly Vinyl Fluoride
PV/T	Photovoltaic Thermal
PSA	Pressure Sensitive Adhesive
ROI	Return on Investment
SPP	Simple Payback Period
SWH	Solar Water Heater
UCE	Unit Cost of Energy
USD	United States Dollar
V	voltage (volt)

Subscript

e	electrical
eq	equivalent
mp	maximum point
o	overall
oc	open circuit
p	peak
sc	short circuit
t	thermal

Kirubakaran, 2013). The Levelized Cost of Energy (LCOE) from PV systems in Kenya is estimated at USD 0.21 per kW h in 2011, which is competitive to conventional power systems (Ondraczek, 2014).

For a residential consumer, the electric low temperature shower consumes the maximum power among several household water heating systems (Taborianski and Prado, 2004). The savings in a solar water heater compared to a conventional system is about 80% with electricity or diesel backup (Kalogirou, 2009; He et al., 2011) and is about 75% with both electricity and diesel backup (Soteris, 2004). The performance of solar water heaters using alternate absorber materials like Galvanised Steel-Aluminium fin and Copper–Aluminium fin were similar to Copper–Copper fin arrangement, with lower capital cost and lesser payback period (Nahar, 2002). Similar comparison done using Copper, Galvanized Steel and selective absorber, proved that selective absorber gave the highest performance and galvanized steel gave the lowest payback period (Ertekin et al., 2008). The economic analysis (Kalogirou, 2009) and the life cycle assessment based on technical and environmental performance were performed for a domestic thermosiphon solar water heating system (Koroneos and Nanaki, 2012). An average savings of 220 MJ in embodied energy with 2.4 years' payback period and an average value of 170 kg CO_2 emission mitigation can be achieved using nanofluid (Faizal et al., 2013). Hot climatic regions demonstrate a lower CO_2 emission (Bessa and Prado, 2015). Life Cycle Impact Assessment (LCIA) reveal that that collectors in parallel connection can improve the environmental impact (Lamnatou et al., 2014, 2015a) while the energy payback time decreases to less than 2 years (Hernandez and Kenny, 2012), and around 0.5 years if recycling is also adopted (Lamnatou et al., 2014). The use of biomass for the auxiliary system provided the greatest environmental benefit in comparison with the other fuels (Zambrana-Vasquez et al., 2015).

Stand-alone hybrid renewable energy systems are more reliable than single energy source systems, by supplying at least 95% of the annual total electric demand of a residential house (Abbes et al., 2014). Small scale combined heat and power (CHP) and solar photovoltaic technologies provide significant greenhouse gas emission reductions at the residential level (Nosrat et al., 2014). A 300 m^2 PV/T system was analysed in TRNSYS software for industrial applications provided electricity and hot water above 60 °C simultaneously (Kalogirou and Tripanagnostopoulos, 2007). Hence, there is a need for more LCA studies in hybrid renewable energy technologies (Lamnatou et al., 2015b).

As per the literature survey, a fascinating amount of research papers are available regarding economic analysis and environmental impact of solar PV systems and solar thermal systems. However, the number of publications in hybrid technology is limited; also, a comparative study on the different solar energy systems available to the domestic consumer is unavailable as per the authors' knowledge. Solar energy systems are considered an investment because of its long lifetime of more than 25 years producing energy at negligible maintenance cost. The CO_2 mitigation by the use of solar technologies surpasses the embodied CO_2 emission. But the high embodied energy in the solar technologies increases the cost and payback period of the system. But, higher initial investment and a lack of awareness are the bottlenecks for the success of solar in the residential sector. Hence, the economics of the solar energy system has to be understood and calculated to determine the feasibility of the installation. In this paper, the energy, mass, cost, embodied energy, embodied CO_2 emission and economics of a new solar PV/T collector are compared with a solar flat plate collector and a solar PV module of the same collector area. The new PV/T collector was also compared with the conventional PV/T collector. All the three solar energy systems considered in this study are off-grid solar energy systems catering to the needs of the residential consumer.

2. Method

A commercially available flat plate 100 LPD solar water heating system and a mono-crystalline 325 W_P PV system, each having an aperture area of 2 m^2 (approximately) were compared to a flat plate 100 LPD solar PV/T water heating system. A similar comparison having the equal collecting areas was experimentally tested