

Energy and exergy efficiency of water-based photovoltaic thermal (PVT) systems: an overview

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Article Info

Article history:

Received Aug 15, 2018

Revised Nov 19, 2018

Accepted Jan 28, 2019

Keywords:

Energy analysis

Exergy analysis

Photovoltaic

Renewable energy

Solar energy

ABSTRACT

Conventional fuels are not free, scarce and expensive, and its future cost and availability are uncertain. Hence, the usage of solar energy in applications will probably increase and further become economically feasible in the near future. Solar energy is free, clean, and renewable and has been widely used in electricity generation and thermal energy via photovoltaic thermal (PVT) system. PVT is a hybrid system consists of a PV panel and a solar collector in a single unit to simultaneously produce electricity and thermal energy. In this review, energy and exergy efficiency for water-based PVT systems is presented. As conclusion, the study on exergy is still limited and is recommended to be furthered in order to obtained useful energy generation by the system.

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1. INTRODUCTION

These past days has governed the advancements of technologies by sourcing solar energy as the energy input. Due to the sustainability of solar source, the renewability of the energy had contributed to the employment of them in most of recent applications. The most promising technology that made great pace in advancement is photovoltaic (PV) technology which using solar panel in converting sunlight to electrical energy. As further studies has been continued, photovoltaic thermal (PVT) system has been introduced which is the combi system of PV and heat collector system. The PV panel absorbs the solar radiation while the heat collector system acts as to remove heat from the PV to regulate the temperature of panel, avoiding extreme hot condition of panel during the operation. Thus, PVT system produces both electrical and thermal energies from one integrated system; drawing high attention from lots of studies regarding its prospects in fullfilling the energy demand. PVT system is a promising system to generate both energies due to its high reliability system with low environment impact. Primarily, the focus of study was on glazed collectors or panel; both air-based and water-based system.

The differences were the coolants used either air or water in the heat collector or cooling system. Among the application of these systems as had been used for building integrated photovoltaic thermal (BIPVT) system. Generally, a water-based PVT system comprising with PV module, absorber collector in the designated tubes, the glass cover, and insulated container. An air-based PVT system consists of a PV panel and a thermal collector system. The system can produce electrical energy directly converted from solar radiation, while extracting heat from the PV panel and warm the air flow inside the collector; as

well as for utilizing water in water-based PVT system. These explain the production of hot air and hot water from the water-based and air-based PVT systems [1–15].

In the mid-1970s, a study with the focus on PVT systems, aiming to increase the PV efficiency had been carried out. In the meantime, to meet the deployment of the technology in domestic application was regarded as the main market [16]. In this review, energy and exergy efficiency of water-based PVT systems is presented, and types of water-based PVT system is described.

2. TYPES OF WATER-BASED PVT SYSTEMS

Utilization of water as coolants in PVT systems which also known as water-based PVT systems had been experienced great advancements. Based on the researches that had been conducted as shown in Figure 1, flow pattern of coolant in water-based PVT systems can be categorised into three types are: (i) natural flow, (ii) force flow and (iii) hybrid system.

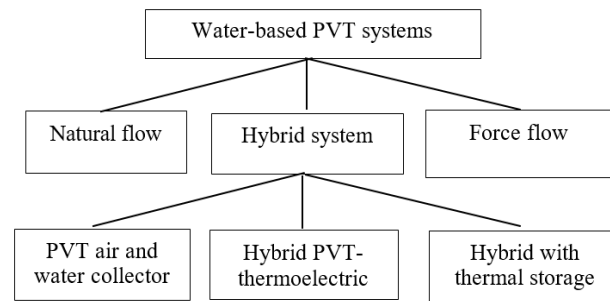


Figure 1. Classifications of flow pattern in water-based PVT systems

3. STUDIES CONDUCTED ON WATER-BASED PVT SYSTEMS

Afterwards, an evaluation of combined PVT systems also had been carried out by Hendrie [17] which the performances of both electrical and thermal energy had been evaluated by yielding sharp relation to the theoretical results. From the research, it had proved that PVT collector system can assured in having potential for useful and greater thermal and electrical energy gain. From his theoretical studies, he also concluded that the analytical models can be used in predicting the energy production's performances as it gave an accurate data.

An experimental study also had been conducted by Erdil et al. [18] which focused on energy generation with a PV- solar thermal hybrid system by using water as coolants. Two experimental modules had been used as the hybrid system while input/output diverse system had been installed in order to ensure constant flow circulation of water across the cavity.

First, the investigation on water-based PVT systems under continuous assortment of temperature mode with unlike constant flow rate mode by Mishra and Tiwari [19] had been compared for two panel's configuration which partially covered and fully covered PV module. The partially covered PV had been shown that the case was preferable for hot water or high thermal yield production meanwhile the one with fully covered resulted in generating higher electrical gain, hence better for primary requirement of obtaining high electrical gain.

Chow et al. [20] also had studied dissimilar water-based PVT system which resulting that unglazed PVT generated higher thermal energy than glazed PVT. Other than that, Shyam et al. [21] had concluded from a study on partially covered PV module of water-based PVT system connected in series, that the temperature reliant on module efficiency, tank and outlet water temperature have been validated for the water-based PVT system.

Other than that, exergy efficiency was investigated experimentally and mathematically which more realistic and practical view of process than energy analysis method [22]. Agrawal and Garg [23] also have studied the energy performance a water-based PVT system. Difference method had been used to simulate the performance of the water-based PVT system. Their results indicated that water-based PVT systems generated satisfactory electrical energy for domestic usages.

4. ENERGY AND EXERGY EFFICIENCY OF WATER-BASED PVT SYSTEMS

Exergy theory also had been used in term of attaining analysis on performance of water-based PVT system, experimentally. From their annual experimental assessment, they determined that the water-based PVT system can produce better exergy output than a unit of PV module or water collector [24]. Tiwari and Sodha [25] also had established a thermal model for a water-based PVT system and conveyed that a daily thermal efficiency of around 58% had been achieved. Dubey and Tiwari [26] have designed and verified an unsteady state system of water-based PVT system. An observation of it performed better thermal and average cell efficiency which is in accordance with previous research. Then, Tiwari et al. [27] had come to conclude that the overall exergy and thermal efficiency of PVT system is maximum at mass flow rate of 0.006 kg/s.

In 2014, a thermal model had been designed to test for electrical efficiency of a-Si PV module. Water flow had been implied on the front of panel in open loop condition for cooling the PV module. Water flow over the PV module had been concluded as improving its efficiency as this design was where the drained water, had been unused and also without integrating it with any plate water collector assembly [28]. Then, in the same year, it had been approved by Herrando et al. [29] that water is the best heat removal compared to air. A presentation of a numerical model had been studied by Boubekri et al. [30] to testify the electrical performance of a collecting hybrid water-based PVT system which it had been shown that the overall efficiency of the collector also can be influenced by the inclination angle, the mass flow rate of water and the conduction heat transfer coefficient in the adhesive layer.

Kalogirou et al. [31] also led a simulation on the industry of PVT systems with water heat extraction in three places with different latitudes, and also using different type of solar cells. The previous study had approved on the water efficiency as heat extraction and as well as latitudes that influences the energy generation. Meanwhile, as for this study which used different solar cells, it had been emerged that the electricity generation is higher for polycrystalline solar cells whereby amorphous solar cells produced slightly higher thermal contributions. Beforehand in 2006, a computer simulation was performed which concentrating on the combined effects of solar cell packing factor and water mass flow rate. These factors were the variables to study on the electrical and thermal efficiencies. It had reconfirmed that system operation at the optimum mass flow rate improved the thermal performance. However, it then lessening when a critical mass flow is surpassed [32]. Energy and exergy analysis of water-based PVT systems by different researchers as shown in Table 1.

Table 1. Performances of water-based PVT systems

Year	Author(s)	Study	Performance Analyses	Energy Efficiencies (%)			PVT Exergy Efficiency (%)
				Thermal	PV	Overall	
1994	Garg et al. [33]	Experimental	Energy analysis	55	9	65	NA
2001	Huang et al. [34]	Experimental	Energy analysis	38.9	9	47.5	NA
2002	Staebler et al. [35]	Experimental	Energy analysis	32.5	18.6	NA	NA
2003	Chow [36]	Experimental and theoretical	Energy analysis	NA	10.2	NA	NA
2006	Chow et al. [37]	Experimental	Energy analysis	57.4–76.3	12.1–12.3	69.7–76.3	NA
2006	He et al. [38]	Experimental	Energy analysis	55	11.5	58	NA
2006	Tiwari and Sodha [25]	Experimental and theoretical	Energy analysis	77.25	11.88	58	NA
2007	Chow et al. [39]	Experimental	Energy analysis	38.9	8.56	NA	NA
2007	Ji et al. [40]	Experimental and theoretical	Energy analysis	45	10.1	52	NA
2007	Fraisse et al. [41]	Experimental	Energy analysis	NA	10	NA	NA
2009	Dubey and Tiwari [42]	Experimental and theoretical	Energy analysis	16.8–33.1	NA	NA	NA
2009	Cristofari et al. [43]	Experimental	Energy analysis	55	12	68	NA
2011	Dupeyrat et al. [44]	Experimental	Energy analysis	79	8.8	88	NA
2011	He et al. [45]	Experimental	Energy analysis	40	9.8	51	NA
2011	Gang et al. [46]	Experimental	Energy–exergy analysis	41.9	9.4	NA	6.8
2011	Wu et al. [47]	Experimental and theoretical	Energy–exergy analysis	63.65	8.45	NA	10.26
2012	Gang et al. [48]	Experimental and theoretical	Energy analysis	23–38	1.5–4.3	NA	NA
2012	Kim and Kim [49]	Energy analysis	Energy analysis	51	14.3	65.3	NA

Energy and exergy efficiency of water-based photovoltaic thermal...(Nurul Shahirah Binti Rukman)

Table 1. Performances of water-based PVT systems

Year	Author(s)	Study	Performance Analyses	Energy Efficiencies (%)			PVT Exergy Efficiency (%)
				Thermal	PV	Overall	
<i>(Cont.)</i>							
2012	Kim and Kim [50]	Experimental	Energy analysis	66–70	14–15	70–85	NA
2012	Cristofari et al. [51]	Experimental	Energy analysis	29	14	43	NA
2013	Dubey and Tay [52]	Experimental	Energy analysis	39.4–40.7	11.4–11.8	NA	NA
2013	Mishra and Tiwari [19]	Experimental	Energy–exergy analysis	28.2–45.9	10.0–10.4	NA	NA
2013	Axaopoulos and Fylladitakis [53]	Theoretical	Energy–economic analysis	17.7	NA	NA	NA
2014	Ibrahim et al. [54]	Experimental	Energy–exergy analysis	55–62	11.4	NA	12.0–14
2014	Fudholi et al. [55]	Experimental	Energy analysis	54.6	13.8	68.4	NA
2015	Aste et al. [46]	Experimental and theoretical	Energy analysis	28.8	13.2	42	NA
2015	Good et al. [57]	Experimental	Energy analysis	71.5	17.4	NA	NA
2015	Shyam et al. [58]	Theoretical	Energy analysis	44.6–49	10.2–10.8	NA	NA
2015	Tiwari et al. [59]	Experimental and theoretical	Energy–exergo–economic–enviro-economic analysis	NA	13.4–23.2	28.5–53.4	NA
2016	Aste et al. [60]	Experimental and theoretical	Energy analysis	20.8–45	13.4–13.7	32.7–40.6	NA
2016	Rosa-Clot et al. [61]	Experimental	Energy analysis	62	13.19	NA	NA
2016	Tse et al. [62]	Theoretical	Energy–economic analysis	NA	16	NA	NA
2016	Yazdanifard et al. [63]	Theoretical	Energy–exergy analysis	70	17	NA	NA
2016	Singh et al. [64]	Experimental and theoretical	Energy–exergy analysis	69.06	NA	75	NA
2016	Tripathi et al. [65]	Experimental and theoretical	Energy–exergy–enviro-economic analysis	40–50	NA	45–63	NA
2016	Xu et al. [66]	Experimental and theoretical	Energy analysis	60	28	NA	NA
2017	Aste et al. [67]	Experimental	Energy analysis	29.4	6.0–14.2	42.3–52.6	NA
2017	Hui et al. [68]	Experimental and theoretical	Energy analysis	35	10	NA	NA
2017	Modjinou et al. [69]	Experimental and theoretical	Energy analysis	54	7.6	NA	NA
2017	Liang et al. [70]	Experimental and theoretical	Energy analysis	45–62	14.25–15.92	NA	NA
2017	Lari and Sahin [71]	Experimental and theoretical	Energy–exergy–economic analysis	NA	13.2	NA	NA
2017	Salem et al. [72]	Experimental	Energy–exergy analysis	31.6–57.9	17.7–38.4	59.3–92	11.1–13.5

5. CONCLUSION

In this review, water-based PVT systems had been summarized which comprising the studies that had been carried out previously on the advancement of this system. Production of hot water, portrayed by the thermal gain more than 50%. Though, the study on exergy is still limited and is recommended to be furthered in order to obtained useful energy generation by the system.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the funding from the USAID through SHERA program-Centre for Development of Sustainable Region (CDSR). The authors would like to thanks the UKM for support.

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BIOGRAPHIES OF AUTHORS



Nurul Shahirah binti Rukman, graduated in bachelor degree of Applied Physics from Universiti Sains Islam Malaysia (USIM) 2017. Focusing on PVT energy generation during her final year study had influenced her to further the study of PVT technology system. Currently, has been under supervision of Dr Ahmad Fudholi for her Master degree (Renewable Energy), on exergy-environmental-economic analysis of bi-fluid PVT system.). She has published more than 5 peer-reviewed papers in journals are in the Scopus and WoS index.



Ahmad Fudholi, Ph.D, M.Sc obtained his S.Si (2002) in physics. He was born in 1980 in Pekanbaru, Indonesia. He served as was the Head of the Physics Department at Rab University Pekanbaru, Riau, Indonesia, for four years (2004–2008). A. Fudholi started his master course in Energy Technology (2005–2007) at Universiti Kebangsaan Malaysia (UKM). After obtaining his Master's, he became a research assistant at UKM until. After his Ph.D (2012) in renewable energy, he became postdoctoral in the Solar Energy Research Institute (SERI) UKM until 2013. He joined the SERI as a lecturer in 2014. He received more than USD 400,000 worth of research grant (16 grant/project) in 2014–2018. He supervised and completed more than 30 M.Sc projects. To date, he has managed to supervise eight Ph.D (six as main supervisors and two as co-supervisor), one Master's student by research mode and one Master's student by coursework mode. He was also an examiner (five Ph.D and one M.Sc). His current research focus is renewable energy, particularly solar energy technology, micropower systems, solar drying systems and advanced solar thermal systems (solar-assisted drying, solar heat pumps, PVT systems). He has published more than 120 peer-reviewed papers, of which 30 papers are in the ISI index (25 Q1, impact factor more than 4) and more than 80 papers are in the Scopus index. He has published more than 80 papers in international conferences. He has a total citations of 1195 and a h-index of 17 in Scopus (Author ID: 57195432490). He has a total citations of 1684 and a h-index of 21 in Google Scholar. He has been appointed as reviewer of high-impact (Q1) journals. He has also been appointed as editor of journals. He has received several international awards. He has also been invited as speaker in the Workshop of Scientific Journal Writing; Writing Scientific Papers Steps Towards Successful Publish in High Impact (Q1) Journals. He owns one patent and two copyrights.



Ivan Taslim, S.Si, M.T from South Sulawesi, Indonesia. He graduated with the M.T in Geology Engineering from University of Hasanuddin in 2014. In 2015, he joined as lecturer at the Department of Geography, Faculty of Science and Technology, University of Muhammadiyah Gorontalo. His main areas of research interest are Management Risk Disaster, Geospatial Data Science and Climate Change with no limited to Renewable Energy. He is currently one of the researchers from USAID SHERA who focuses on developing and using renewable energy in Indonesia. Currently, he is entrusted to work with the Gorontalo Regional Government as a staff in the field of Climate Change and Disaster Mitigation.



Merita Ayu Indrianti, S.P., M.P from Banjarmasin South Borneo, Indonesia. She graduated in Agriculture from University of Hasanuddin in 2016. She has working as a lecturer at the Department of Agriculture University of Muhammadiyah Gorontalo since 2014. Her main areas of research interest are Socio-Economic in Agriculture, Biomass and Biogas energy and Integrated Farming System for Food Security. In her career, she had served as secretary of the Agricultural Study Center (2015) and secretary of the Agribusiness study program (2016) in Department of Agriculture.



Intan Noviantari Manyoe, S.Si, M.T from Gorontalo, Indonesia. She was born in 1982, and graduate from University of Hasanuddin with a degree in Geophysics and have a masters in Geology Engineering in 2014. She is working as a lecture at the Department of Geology also Head of Geology Engineering Laboratory at University State of Gorontalo. Her main areas of research interest are Geophysics, Tectonic, Volcano and Geothermal.



Uce Lestari, S.Farm, M.Farm, Apt obtained his S.Farm (2004) in Pharmacy Technology. She was started his master course in Clinical Pharmacy (2008–2010) at Universitas Andalas. She joined the Faculty of Science and Technology, University of Jambi, Indonesia as a lecturer in 2014. He received more than USD 12,610 worth of research grant (13 grant/project) in 2014–2018. He supervised and completed of 6 B.Sc projects. His current research focus Clinical and Pharmacy Technology and, particularly utilization of palm kernel shells into a pharmaceutical product technology product that is beneficial to society. She has published more than 23 papers are in the journals and conferences.



Prof Dato' Dr. Kamaruzzaman Sopian graduated with BS Mechanical Engineering at the University of Wisconsin-Madison in 1985, MS in Energy Resources at the University of Pittsburgh in 1989 and PhD in Mechanical Engineering at the Dorgan Solar Laboratory, University of Miami at Coral Gables in 1997. He has been involved in the field of renewable energy for more than 25 years. He has secured research funding of more than USD 6 million from the Malaysian Ministry of Science and the Malaysian Ministry of Education as well as from the industry. He has conducted renewable energy courses in the Asian School of Energy (2007–2014), which was funded by ISESCO, COMSAT, TIKa and UNESCO. He has published over 700 papers in journals and conferences (SCOPUS h index = 57, no. of citations = 11245; Google Scholar h index = 69, no. of citations = 18048). He supervised and completed 32 MSc (coursework), 15 MSc (research mode) and 40 PhD students.