Innovative Photovoltaic Cooling System (IPCoSy)

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The field efficiency of silicon-based solar cells is dependent on various factors, including temperature. An increase in temperature results in a reduced efficiency of a magnitude dependent on the solar cell's temperature coefficient. Furthermore, an increase in solar cell temperatures beyond levels specified by the manufacturer will result in a reduced lifetime and an increased probability of potential induced degradation and even failure. A patented Innovative Photovoltaic Cooling System (IPCoSy) is presented here. The full-scale prototypes are the same size as commercially available photovoltaic modules, making them easier to integrate in the current market. Designs can be commercially viable, especially when coupled with other systems such as reverse osmosis plants and water heating.

solar energy | photovoltaics | cooling technology | photovoltaic thermal | thermal energy

1. Introduction

Photovoltaic (PV) power output is dependent on the absorbed incident solar radiation by solar cells, the efficiency and temperature coefficient of the solar cell material, and the operating temperature of the photovoltaic module. Various solutions have been proposed to optimize the absorbed incident solar radiation such as through the use of tracking mechanisms and anti-reflective coatings. Similarly, materials research has advanced the efficiency and temperature coefficients of solar cells. This research presents an innovative method to decrease the operating temperature of photovoltaic modules, and, as a result, increase their efficiency. The dependence of the efficiency on temperature is given in Equation (1) [1]. Here, n_c and n_{Tref} are the solar cell conversion efficiencies at a particular cell temperature and at reference temperature, respectively. β_0 is the PV module's temperature coefficient (example: 0.48%/K) and $T_c - T_{ref}$ shows the temperature difference between the cell temperature and the reference temperature [1].

$$n_c = n_{Tref}\left[1 - \beta_0\left(T_c - T_{ref}\right)\right]$$

An increase in temperature causes an increase in electron energy in the valence band. This results in a decrease in the material's band gap since the energy gap between the conduction band and the valence band is narrowed [1]. Furthermore, this leads to higher intrinsic carrier concentrations, which results in an increase in the dark saturation current of the p-n junction [1]. A study by Wen Cai et al. [2] showed that the temperature effect on the short circuit current of a solar cell differs for single crystalline and polycrystalline silicon. In single crystalline silicon, the short circuit current decreases with temperature due to an increase in thermal lattice vibrations, which hinders carrier mobility. Polycrystalline silicon solar cells exhibit a slight increase in short circuit current with an increase in temperature. This effect arises partly from the decreasing band gap, which results in additional lower energy photons being absorbed and converted to charge carriers. However, this effect can also be observed in single crystalline silicon, and, in both cases, it plays a minor role. The major temperature effect in polycrystalline silicon is attributed to the ratio of recombination area decreasing at a fast rate with increasing temperature. Therefore, this leads to increased carrier mobility, which translates to an increase in the short circuit current [2]. Although the short circuit current in polycrystalline silicon solar cells can increase by 0.1% per °C, the reduction in open-circuit voltage contributes to a net decrease in the maximum power that the solar cell can deliver [3]. Elevated PV operational temperatures result in a faster degradation rate, which is even higher in open-circuit conditions [4]. This is especially true in hot climates, and, in tropical environments, PV temperatures can even exceed the maximum temperature thresholds set by the manufacturer, possibly resulting in permanent damage to the PV module [5].

Hence, it is beneficial to find a solution to lower the PV operational temperature through cooling methods. This study presents an innovative back-side water-cooling system due to its various benefits both offshore and on land. The cooling system, termed IPCoSy, involves a water chamber fitted in the space conventionally available at the back of PV modules, inside the aluminium frame, as shown in **Figure 1**. Whenever the controlled cooling flow is initiated, the warm water inside the cooling chamber is replaced with cooler water, resulting in a drop in the PV operating temperature. Furthermore, since the cooling water remains in contact with the back of the PV module after the cooling flow is stopped, the added specific heat capacity results in the PV module taking longer to heat up. Therefore, this cooling system requires a lower pump-switching frequency resulting in less power consumption and a longer pump lifetime. This hypothesis and the cooling system feasibility were confirmed in a previous small-scale study [6]. The small-scale study concluded that IPCoSy could achieve gains in energy yield of up to 10% with a controlled water flow and up to 3% without flow. However, this study utilised small-sized PV panels that had few commercial applications. This article presents a study aimed at designing and testing commercial size prototypes addressing challenges such as structural integrity, fluid dynamics, and the optimisation of the pump power to PV power ratio. The IPCoSy designs can be commercially viable, especially when coupled with other systems such as reverse osmosis plants and water heating. The designs and applications presented in this study are protected by an international patent [7].

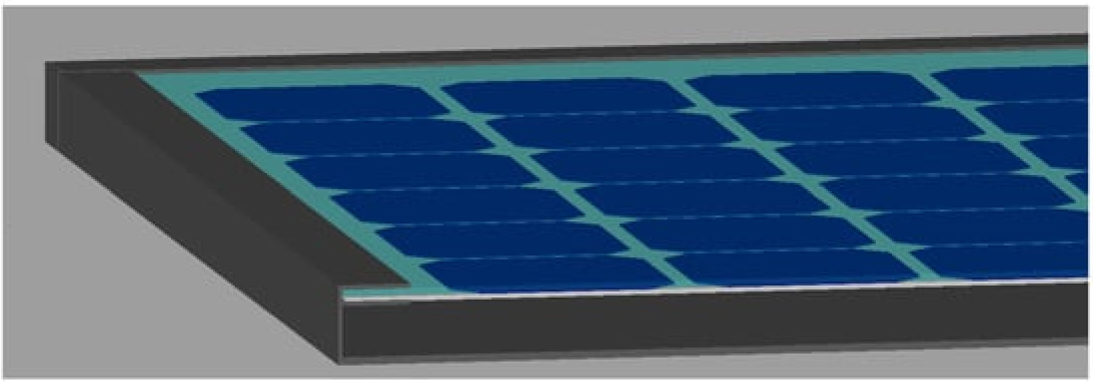

Figure 1. Cross-section showing one of the IPCoSy designs.

2. Innovative Photovoltaic Cooling System (IPCoSy)

The cooling of PV modules can be achieved through various methods such as forced air cooling, water cooling, thermoelectric cooling modules (TEMs), natural cooling, Phase Change Materials (PCMs), and heat sinks [3]. Passive air cooling is a cost-effective method to cool PV panels. However, the low density, thermal conductivity, and volumetric heat capacity of air result in poor thermal performance, making passive air cooling insufficient [8]. Forced (active) air cooling shows an improvement in thermal performance when compared to natural (passive) air cooling [3]. Teo et al. [9] designed an active PV air cooling system which increased solar cell operating efficiency by 3% to 6%. A well-designed PV/PCM system enables the PVs to operate in near-optimum temperatures while heating buildings at night by releasing the thermal energy stored in the PCM [10]. For a material to be adequate for use as a PCM, it must have a high thermal conductivity and a large latent heat [11]. The increase in annual energy output with the introduction of PCM with solar modules was investigated [12]. This study also identified the optimal PCM melting temperatures for different locations globally. It was found that PCM is viable mainly in places with very high insolation and little variability. Using PCM would thus increase the annual PV energy output by more than 6% in Mexico and Eastern Africa, 2–5% in Europe, and over 5% in most other locations [12]. Other systems combine PV panels, heatsinks, and TEMs [13][14]. These systems use thermoelectric modules to dissipate heat from the PV modules. Furthermore, heatsinks are used to dissipate heat from thermoelectric modules. This creates a temperature difference across the TEM, which results in the diffusion of charge carriers within the TEM materials. This results in the TEM producing power in addition to increased PV module efficiency. This setup reported a maximum decrease in PV temperature of 8.29 °C.

Water cooling is one of the most viable solutions for controlling the temperature of PV modules because of the high specific heat capacity of water. Furthermore, a water cooling technology is ideal to implement on offshore or floating PV installations due to the very large water resources available. However, when adopting a forced convection PV cooling system, one must strike a balance between increased PV efficiency due to lower temperatures and power consumed by a pump, fan, or any other device used to force convection. A study [15] determined that the ideal temperature to start cooling PVs is 45 °C, and cooling should continue until the PV module reaches a temperature of 35 °C. Water cooling can either be applied to the front or the back side of a PV module. A water film on the front side of a PV module is sometimes used to create the desired cooling effect. Furthermore, the water film helps to maintain a clean surface while also creating an anti-reflective coating, thus contributing further to an increase in solar cell operating efficiency. However, when such cooling systems are employed, one must consider power consumption by the pump and water consumption due to evaporative losses [8]. S. Nižetić et al. presented a study [16] on cooling PVs using front- and back-water spraying in a Mediterranean climate. PV temperature was reduced from 52 °C to 24 °C, with the lower temperature being limited by the temperature of the water. When considering electricity usage to pump water, a maximum of 7.7% effective increase in power output and 5.9% effective increase in efficiency were achieved. An essential improvement in this setup is eliminating the shading caused by the water sprinklers. Shading a PV module with a cooling setup may result in a power loss equal to or greater than the power gained by cooling. Furthermore, shading may cause mismatch issues on larger PV plants. Another study [17] examined the performance of a PV water pumping system with the PV module cooled by front water spraying. A maximum temperature reduction of 23 °C was achieved due to water spray and evaporative cooling. This cooling methodology increased the mean PV cell efficiency by 3.26%, and an increase in the measured short circuit current implied an improved optical performance due to the water spray on the front surface.

One of the challenges of front-side water cooling is that the water can evaporate and stain the front glass with limescale or salt if utilising seawater. Limescale build-up occurs due to the formation of calcium and magnesium carbonates. Besides being difficult to clean, this deposit can also block some of the transmission of solar radiation to the solar cells, decreasing the efficiency of the photovoltaic module. Farrugia et al. [18] quantified the loss due to limescale build-up, which amounted to an average decrease of 2.38% in daily energy yield. Furthermore, front-side water cooling can lead to a high evaporation rate [19]. Therefore, cooling water must be replenished frequently, especially in locations where rainfall is scarce.

Various studies investigate the use of heat exchangers installed at the back of the PV module to create what is referred to as photovoltaic thermal (PVT) systems. A PVT collector consists of a PV module with fluid flowing through structures underneath the PV to absorb heat from this module [20]. The driving factor for research in PVTs is that approximately 78% of the incident solar radiation on a PV module is transformed to heat energy and not electrical energy [8]. There are two main types of PVT configurations, namely open-loop and closed-loop [21]. In an open-loop configuration, the fluid is passed once underneath the PV at a set flow rate, and the heat absorbed by the fluid is utilised instantly. An application of an open-loop PVT system is in residential direct space heating [21]. On the other hand, a closed-loop PVT system incorporates a circulating pump, which passes the fluid several times underneath the PV module to increase the amount of heat absorbed by the fluid [21]. A typical application of a closed-loop PVT system is in residential water heating. When opting to maximise PV output efficiency, open-loop PVT systems are preferred since a closed-loop system favours water heating, which would lead to the PV module reaching very high temperatures. This leads to a decrease in PV efficiency and possible delamination. A closed-loop PVT solar collector in thermosiphon mode was studied [22], achieving an electrical power enhancement of 1.56% and a thermal efficiency of 10.73%. The negligible electrical power enhancement shows that a closed-loop system does not favour PV temperature and PV electrical efficiency. Cooling channels installed at the back of PV modules can be made of various materials. However, although plastic materials are easy to use, they have poor thermal conductivity, resulting in a low heat loss coefficient. Hence, metal ducts are preferred, and, in a particular study, these yielded a heat transfer coefficient of 45.09 W/m^2 [23]. In addition to metallic ducts, this study installed a metal sheet on the back-side of the PV panel to cool the back of the PV module uniformly. Zondag et al. [24] compared four groups of combined PVT systems. The two-absorber PVT collector yielded the highest thermal efficiency of 65–66%, while the sheet and tube PVT collector yielded the highest electrical efficiency. A feasibility study by Rebollo et al. [25] gives PV module temperature and efficiency priority over hot water generation. In this study, rectangular aluminium channels were installed at the back of the PV module, resulting in a 2% increase in electrical efficiency. However, the author argues that the most significant limiting factor for heat transfer was the poor contact between the aluminium channels and the PV module. Another study [26] utilised a Solar Nor collector made from Poly(p-phenylene oxide) (PPO) plastic channels filled with ceramic granulates to cool a combination of solar cells pasted on an absorber plate. A high heat-transfer resistance was identified as one of the key factors contributing to reduced thermal efficiency compared to a conventional thermal absorber. H. Bahaidarah et al. [27]

constructed a numerical model and verified it experimentally by installing a solar-thermal collector at the back of the PV module. This active cooling experiment achieved a 20% temperature drop and a 9% increase in PV panel efficiency. In another study [19], ice was also used to keep a continuous flow of water cool on the front of a PV module. This setup observed a maximum instantaneous power improvement of 24%.

Most existing cooling systems do not address the issue of a rapidly increasing PV temperature as soon as the forced cooling flow is stopped. This will lead to a high pump-switching frequency and increased power consumption, making it difficult for the cooling system to become financially viable while decreasing the lifetime of the water pump. The state-of-the-art research has a gap when it comes to finding a feasible cooling system that does not impact incident solar radiation and does not require a high pump-switching frequency, resulting in an efficient cooling flow.

This research presents the outcomes of testing a patented photovoltaic back-side cooling technology. The results showed that when a controlled flow is applied to the IPCoSy photovoltaic modules, energy yield gains of up to 9.02% are possible. Furthermore, this research showed that energy gains are also possible when simply filling the cooling chamber with water without any further controlled flow. Under these conditions, IPCoSy achieved energy yield gains of up to 4% when compared to a standard PV module. Furthermore, IPCoSy can be coupled with existing water heating systems in order to feed water at a higher temperature. This study showed that maximum thermal efficiencies of 55.88% are possible.

References

1. Chander, S.; Purohit, A.; Sharma, A.; Arvind; Nehra, S.; Dhaka, M. A study on photovoltaic parameters of mono-crystalline silicon solar cell with cell temperature. Energy Rep. 2015, 1, 104–109.
2. CWen, C.; Fu, C.; Tang, J.; Liu, D.; Hu, S.; Xing, Z. The influence of environment temperatures on single crystalline and polycrystalline silicon solar cell performance. Sci. China Phys. Mech. Astron. 2012, 55, 235–241.
3. Shukla, A.; Kant, K.; Sharma, A.; Biwole, P.H. Cooling methodologies of photovoltaic module for enhancing electrical efficiency: A review. Sol. Energy Mater. Sol. Cells 2017, 160, 275–286.
4. Boussaid, M.; Belghachi, A.; Agroui, K.; Abdelaoui, M.; Otmani, M. Solar cell degradation under open circuit condition in out-doors-in desert region. Results Phys. 2016, 6, 837–842.
5. Hasanuzzaman, M.; Malek, A.B.M.A.; Islam, M.M.; Pandey, A.K.; Rahim, N.A. Global advancement of cooling technologies for PV systems: A review. Sol. Energy 2016, 137, 25–45.
6. Bugeja, R.; Stagno, L.M.; Niarchos, I. Photovoltaic backside cooling using the space inside a conventional frame (IPCOSY). Future Energy 2023, 2, 20–28.

7. Bugeja, R.; Stagno, L.M. System for Cooling a Solar Panel Assembly. 285827, 24 August 2021. Available online: https://israelpatents.justice.gov.il/en/patent-file/details/285827 (accessed on 22 June 2023).
8. Dupré, O.; Vaillon, R.; Green, M.A. Thermal Behavior of Photovoltaic Devices; Springer: Berlin/Heidelberg, Germany, 2017.
9. Teo, H.G.; Lee, P.S.; Hawlader, M.N.A. An active cooling system for photovoltaic modules. Appl. Energy 2012, 90, 309–315.
10. Huang, M.J.; Eames, P.C.; Norton, B. Thermal regulation of building-integrated photovoltaics using phase change materials. Int. J. Heat. Mass. Transf. 2004, 47, 2715–2733.
11. Farid, M.M.; Khudhair, A.M.; Razack, S.A.K.; Al-Hallaj, S. A review on phase change energy storage: Materials and applications. Energy Convers. Manag. 2004, 45, 1597–1615.
12. Smith, C.J.; Forster, P.M.; Crook, R. Global analysis of photovoltaic energy output enhanced by phase change material cooling. Appl. Energy 2014, 126, 21–28.
13. Pang, W.; Liu, Y.; Shao, S.; Gao, X. Empirical study on thermal performance through separating impacts from a hybrid PV/TE system design integrating heat sink. Int. Commun. Heat. Mass. Transf. 2015, 60, 9–12.
14. Siecker, J.; Kusakana, K.; Numbi, B.P. A review of solar photovoltaic systems cooling technologies. Renew. Sustain. Energy Rev. 2017, 79, 192–203.
15. Moharram, K.A.; Abd-Elhady, M.S.; Kandil, H.A.; El-Sherif, H. Enhancing the performance of photovoltaic panels by water cooling. Ain Shams Eng. J. 2013, 4, 869–877.
16. Nižetić, S.; Čoko, D.; Yadav, A.; Grubišić-Čabo, F. Water spray cooling technique applied on a photovoltaic panel: The performance response. Energy Convers. Manag. 2016, 108, 287–296.
17. Abdolzadeh, M.; Ameri, M. Improving the effectiveness of a photovoltaic water pumping system by spraying water over the front of photovoltaic cells. Renew. Energy 2009, 34, 91–96.
18. Farrugia, A. Design and Analysis of Different Cooling Effects on Photovoltaic Panels; University of Malta: Valletta, Malta, 2014.
19. Smith, M.K.; Selbak, H.; Wamser, C.C.; Day, N.U.; Krieske, M.; Sailor, D.J.; Rosenstiel, T.N. Water Cooling Method to Improve the Performance of Field-Mounted, Insulated, and Concentrating Photovoltaic Modules. J. Sol. Energy Eng. 2014, 136, 034503.
20. Dubey, S.; Tiwari, G.N. Analysis of PV/T flat plate water collectors connected in series. Sol. Energy 2009, 83, 1485–1498.
21. Kalogirou, S.A.; Tripanagnostopoulos, Y.; Athienitis, A. Modeling and Simulation of Passive and Active Solar Thermal Systems; Elsevier Ltd.: Amsterdam, The Netherlands, 2012.

22. Arias, H.; Cabrera, J.; Hernandez, J. Performance evaluation of a mono-crystalline PV module cooled by a flat plate solar collector in thermosyphon mode. In Proceedings of the 2015 IEEE 42nd Photovoltaic Specialist Conference, PVSC, New Orleans, LA, USA, 14–19 June 2015.
23. Arcuri, N.; Reda, F.; De Simone, M. Energy and thermo-fluid-dynamics evaluations of photovoltaic panels cooled by water and air. Sol. Energy 2014, 105, 147–156.
24. Zondag, H.A.; de Vries, D.W.; van Helden, W.G.J.; van Zolingen, R.J.C.; van Steenhoven, A.A. The yield of different combined PV-thermal collector designs. Sol. Energy 2003, 74, 253–269.
25. Rebollo, E.; Blanquez, F.R.; Lopez, I.; Platero, C.A.; Carrero, C. Overall feasibility of low cost conversion from PV to PVTw. In Proceedings of the 2013 International Conference on Renewable Energy Research and Applications, ICRERA, Madrid, Spain, 20–23 October 2013.
26. Sandnes, B.; Rekstad, J. A photovoltaic/thermal (PV/T) collector with a polymer absorber plate. Experimental study and analytical model. Sol. Energy 2002, 72, 63–73.
27. Bahaidarah, H.; Subhan, A.; Gandhidasan, P.; Rehman, S. Performance evaluation of a PV (photovoltaic) module by back surface water cooling for hot climatic conditions. Energy 2013, 59, 445–453.