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Citation: AIP Conference Proceedings **1881**, 020008 (2017); doi: 10.1063/1.5001407
View online: http://dx.doi.org/10.1063/1.5001407
View Table of Contents: http://aip.scitation.org/toc/apc/1881/1
Published by the American Institute of Physics

Analysis of Initial Performance of Solergy's HCPV/T System at Rome-Fiumicino International Airport

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Abstract. A commercial HCPV/T system, developed by Solergy, is installed at the airport of Rome, in Italy, as part of a prototype smart grid. The system is rated at 15 kW AC electric and 20 kW thermal and is used to provide both electricity for charging electric vehicles and heat for a conventional thermal power plant. This paper presents an analysis of the performance of the system, operating since March 2017, which achieves a combined peak efficiency of 48%. This study incorporates also an investigation on the improvements that can benefit the system, including a new type of receiver with improved heat dissipation.

INTRODUCTION

One of the main issues affecting the design and the performance of HCPV systems is the production of heat. Indeed, more than half of the radiation reaching the HCPV cell is converted into heat, which can negatively affect the electrical performance [1,2]. Along with the reduction in power output, temperature rise and temperature cycles can cause module degradation and failures [3,4]. Both active and passive cooling technologies have been studied and applied to HCPV systems [5]. In some cases, the heat has been recovered and used for other purposes [6]: this solution is generally called HCPV/T. This approach can enhance the overall system efficiency, since the recovered heat can be employed as an additional energy product [7].

The present paper analyzes the electrical and thermal performance of a HCPV/T system developed by Solergy Italia and installed at Rome's Fiumicino Airport (Italy). A number of works have been presented in the literature where innovative designs are discussed and prototypes are tested, even if only a limited number of studies are focused on field performance [8]. The system installed in Fiumicino offers an occasion to increase the operational experience in HCPV/T and to investigate its applicability in high energy-demanding environments, such as airports. The main scopes of the work are the characterization of the system and the investigation of its current and potential impact on the energy balance of the terminal. Moreover, an analysis of the initial performance and of the improvements that can be applied to optimize the system's operation is presented.

DESCRIPTION OF THE LOCATION AND THE SYSTEM

Fiumicino Airport and the Smart Grid Project

The Solergy system is part of a renewable smart grid demonstration operating at Terminal 1 of the "Leonardo da Vinci" International Airport in Rome, Italy. The terminal 1 serves 16 million passengers and requires a total energy of 23 GWh_e and 35 GWh_{th} per year. The management company of the airport, Aeroporti di Roma (ADR), has

13th International Conference on Concentrator Photovoltaic Systems (CPV-13)
AIP Conf. Proc. 1881, 020008-1–020008-7; doi: 10.1063/1.5001407
Published by AIP Publishing. 978-0-7354-1561-4/$30.00

developed a test smart grid, which includes the HCPV/T system, a 7 kW_t concentrated solar power system, a 3 kW_e and a 10kW_ewind turbines. The electricity generated by the smart grid is used to supply energy to a LED street lighting system as well as four EV charging stations. The heat is employed for the production of domestic hot water.

Solergy's HCPV/T System

The Solergy system, as designed and installed for Fiumicino Airport, is conceived as a combined HCPV/T system, with electrical and thermal ratings of 15 kW_e and 20 kW_{th}. In general, Solergy's technology can be optimized and operated for 1) electric generation only or 2) for cogeneration of electricity and heat (HCPV/T). For cogeneration, total electric output might be slightly compromised in order to increase capture of waste heat. Both modes of operation rely on active cooling.

In this particular case, the application called for both electric and thermal energy streams, and so the system was configured to strike a balance between these two needs. The system is made of 1152 refractive concentrators, each focusing the light on one 1cm^2-sized multi-junction cell at a geometric concentration ratio of 490×. The structure of the system is depicted in Fig. 1: it includes 8 parallel electrical strings, made of 3 series-connected modules each. Each module is made of 48 series-connected cells. The heat produced by the cells is recovered through an active cooling system. A water/glycol solution (90:10) is circulated through a pump and split across the 24 modules (coolant A). From inlet to outlet, each coolant stream cools 48 cells. The thermal power is then transferred from coolant A to a second fluid (fresh water, coolant B), that is then injected into the thermal power plant of the terminal. In order to investigate the performance of the system, a set of dedicated sensors and a data acquisition system have been installed onboard the tracker. The electric data (power and energy) are collected by the inverters and transmitted to a main controller, where they are combined with the instantaneous DNI values. The thermal parameters are monitored by platinum thermal resistance sensors and a flow meter. All data are available in a dedicated Modbus Net and they are uploaded daily into a shared server.

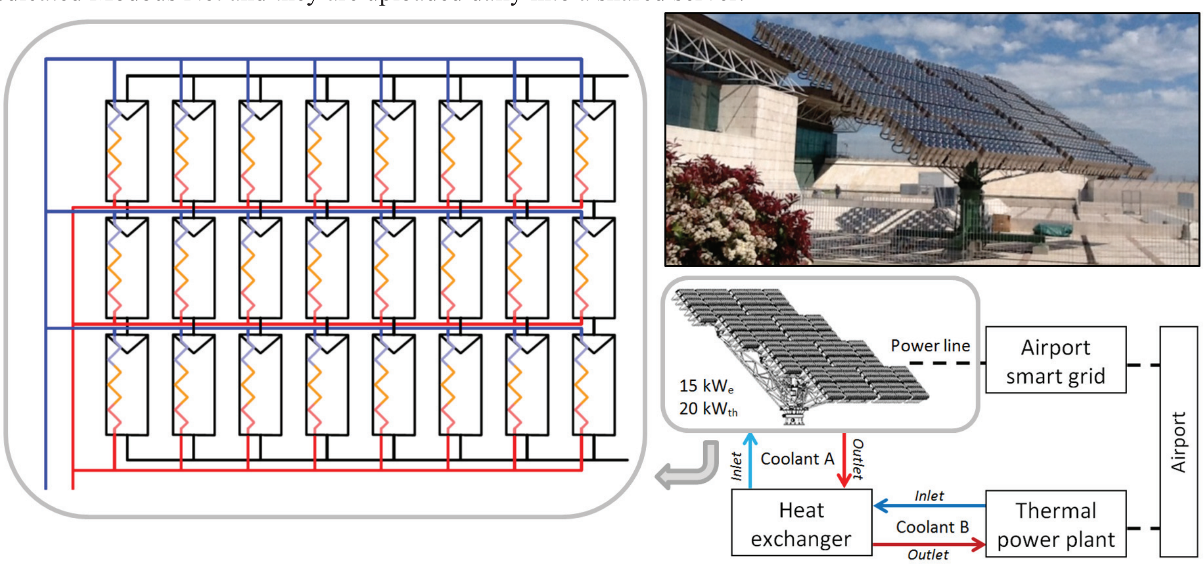

FIGURE 1. Front view and schematic of the Solergy system (left) and block diagram of the tracker energy outputs (lower right). A picture of the Solergy tracker at Terminal 1 of Rome International Airport is shown in the upper right. The nomenclature used to identify the coolants is reported.

PERFORMANCE OF THE SYSTEM

Instantaneous and Monthly Performance

A late winter, clear sky day is considered for this analysis: March 11th, 2017. On that day, the system delivered 105 kWh_e and 100 kWh_{th}. Peak electrical and thermal power output of 12.5 kW_e and 13.7 kW_{th} were measured. The electrical performance of the system is shown in Fig. 2. The power profile matches the DNI performance in the central hours of the day (zenith < 70°) and the performance ratio is constant in this period, with average value of 85%. The performance ratio (PR) tends to linearly decrease when the zenith angle grows from 70 to 80° and drops to zero after that, since the trackers are switched off. Shading from a nearby structure is found to partially affect the system in the morning for 15 minutes.

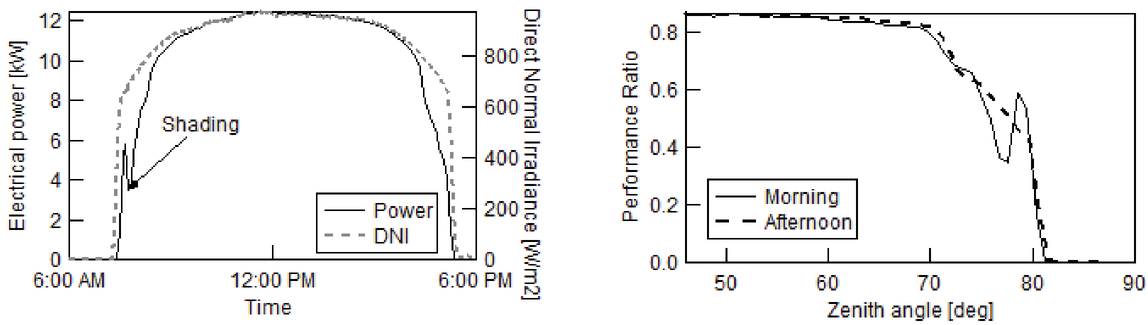

FIGURE 2. Comparison of DC power generated by the Solergy system and the measured direct normal irradiance (DNI) on March 11th, 2017 (left). Performance Ratio of the system plotted against the zenith angle (right) on the same day.

The performance of the Solergy HCPV/T system has been monitored during the months of March and April 2017. Between the 3rd of March and the 24th of April, the system operated consistently and with steady PRs (Fig. 3), generating a total of 3562 kWh of AC electricity.

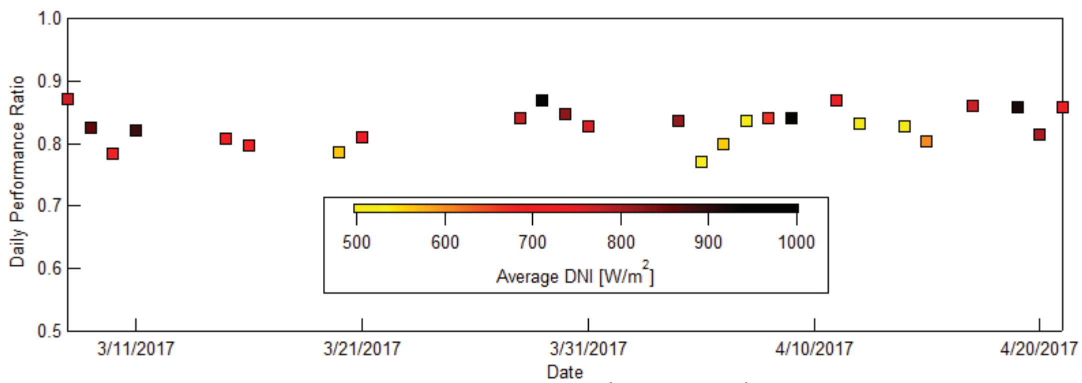

FIGURE 3. AC Performance ratio of the system between March 3rd and April 24th. The markers are colored according to the average DNI registered for zenith < 70°. Days with average DNI < 500 W/m^2 or data acquisition issues are not reported.

The incoming sunlight converted into thermal energy is collected by coolant A and then transferred to coolant B by a heat exchanger. Coolant A resides within Solergy's system, where its flow rate is governed directly by the tracker controller and can be tuned to achieve desired output temperatures. Coolant B is external to Solergy's tracker and its flow parameters are determined by the facility management personnel of Terminal 1. Coolant B is sourced from the standard water supply network and, for this reason, its inlet temperature ranges between 13 and 15°. The thermal system works at an average performance ratio (PR) of 58% if zenith < 70° conditions are considered (Fig. 4). Between 12 PM and 4 PM, the flow rate of coolant B is found to rise from an average of 10 l/min to 15 l/min, causing a reduction of the coolants' temperatures and an increase in average PR to 66%.

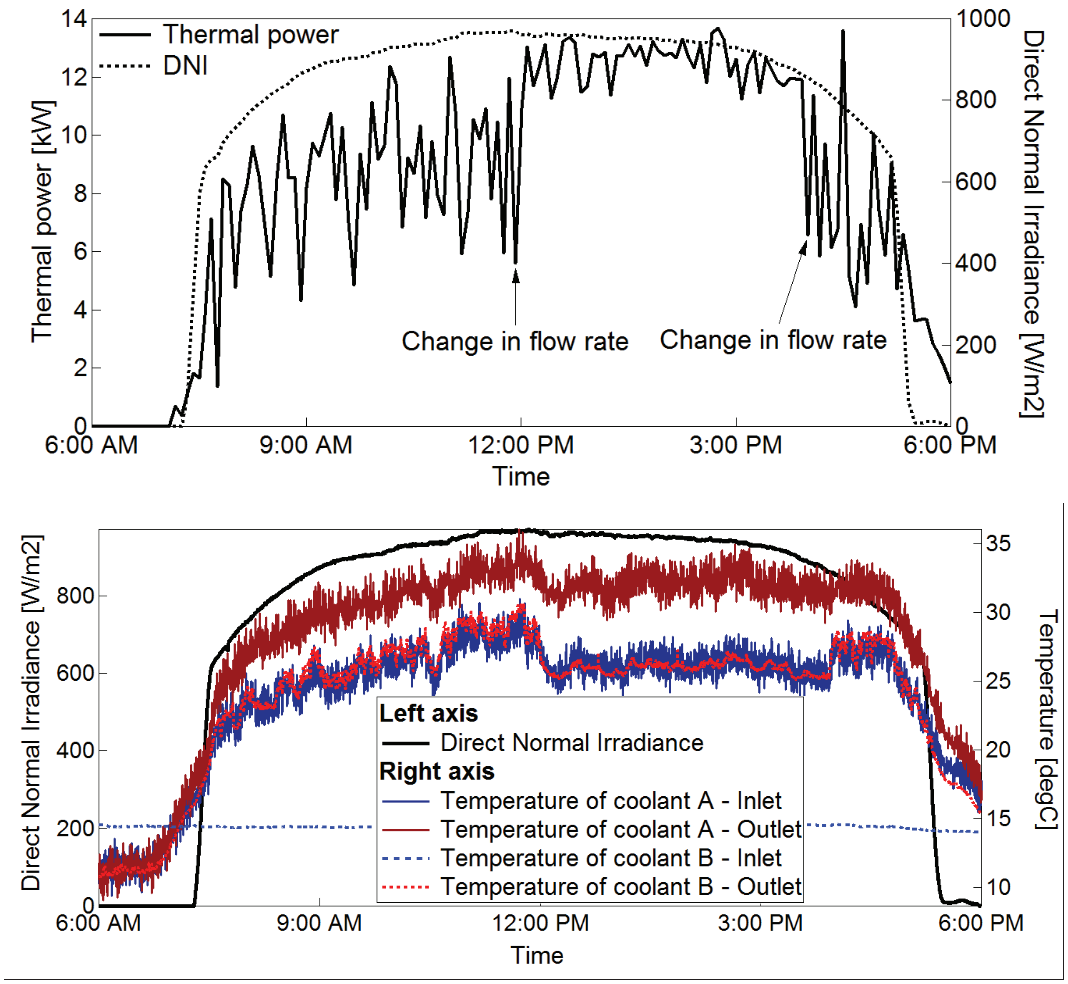

FIGURE 4. Comparison of thermal power generated by the Solergy system and the measured direct normal irradiance (upper) and plot of the temperatures of the coolants (lower) on March 11th, 2017.

The HCPV/T achieves an average overall efficiency of 43.1% for any zenith angle < 70°, with a peak of 48.4% when the flow rate of coolant B is higher. The efficiency is calculated as the sum of electrical and thermal power outputs divided by the product of direct normal irradiance and concentrators' surface. As shown in Fig. 4, the power output of the system could be easily improved by stabilizing the flow rate of Coolant B to a value close to 15 l/min, which, among the flow rates registered during the day, is found to maximize the thermal efficiency of the system.

The HCPV/T and the Electrical Energy Balance of the Terminal

The energy loads of the terminal registered on a day in fall of 2016 were made available and were compared with the energy profile of the HCPV. There is a large difference in scale between the energy loads of the terminal and the energy generated by the HCPV/T system, which has been installed as a pilot test. Indeed, the energy produced by the HCPV system on a clear sky day represents 0.2% and 0.4% of the energy consumed at the terminal in 24 hours and during the sunlight-to-sunset period, respectively. These values are driven by the different sizes of the systems. Despite that, it is interesting to have a look at the power profiles during the day (Fig. 5). The two substations that deliver electricity to the terminal have a flat night consumption rate between 23:30 and 05:00, whose power requirement is 2-3 times lower than the daily use. After that, the power consumption raises and settles between 1.9 and 3.0 MW_e. On March 11th, 2017, the HCPV operated for about 10 hours, all within the airport's peak consumption time period, and, in particular, it worked above the 80% of its peak power for 7½ hours during this time. According to the data available, therefore, the HCPV is actively producing energy during more than 50% of the airport's peak time and for 40% of that time, it is working at its best performance.

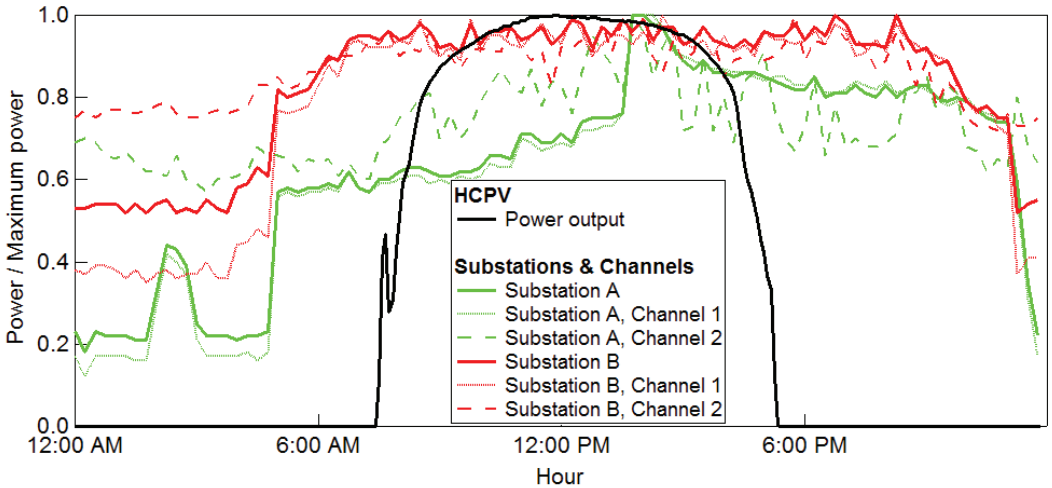

FIGURE 5. Normalized power load and CPV power profiles on October 29th, 2016 and on March 11th, 2017. The electricity is supplied to the terminal through two substations (A and B), each one with two channels (1 and 2).

ANALYSIS OF THE PERFORMANCE AND FUTURE IMPROVEMENTS

Electrical Consumption

The study reported so far has not considered the consumption of the tracker's motors and of the coolants' pumps. These losses have not been directly measured, but can be determined by knowing the size and the time of operation of each component. Also, Solergy performed an accurate analysis of the power consumption of an equivalent HCPV/T system operating at its headquarters in Formello (Rome). The two tracking motors operate continuously for any solar elevation above 10°, consuming 1.7 kWh_e daily. The pump used for coolant A (Pump A) is set at a nominal power of 159 W and is scheduled to work only when a DNI > 0 is measured: a daily energy consumption of 1.7 kWh_e can be assumed. At the moment, the total parasitic losses correspond to 3.3% of the electrical energy produced and 1.7% of the overall energy, reducing the overall average efficiency from 43.1% to 41.4%.

Solergy has recently revised the configuration of the tracker motor drivers, based on the electrical characteristics and the effective torque of the drive chain. According to the test conducted in Formello, the new configuration reduced the energy consumption of the tracking motors to 1.0 kWh_e daily, without any impact on the behavior of the system. Further improvements are expected by replacing the existing motors with new ones now available on the market, using electronics with different technology (system-on-chip) and implementing fine-tuned tracking algorithms. Solergy estimates a daily energy consumption of 0.4 kWh_e for the tracking motors in the next HCPV/T systems. Similar studies are currently in progress to reduce the power absorption of the coolants' pump.

The circuit where coolant B flows is not part of the HCPV/T system and has been installed by the management of the airport to collect the heat from the heat exchanger mounted on the HCPV/T. By taking into account the performance curve of the coolant B's pump (Pump B) and the operating head pressure, it is possible to determine the electrical consumption for any flow rate. The power rate is found to range between 67 and 73 W depending on the flow rate. At the moment this analysis was conducted, Pump B was set to operate 24hr, meaning that it would require 1.7 kWh_e each day, but this value could be reduced to 0.8 kWh_e if the same timing set of Pump A was used for Pump B at a constant flow rate of 15 l/min.

Impact of Cell Temperature

Among the different losses experienced by a HCPV/T system [10], this work focuses on losses related to the temperature of the cells. The power produced by the cells is dependent on their temperature. Having a number of series-connected cells is essential to achieve temperatures that are valuable for domestic hot water applications. The difference in temperature between the coolant A entering and exiting the system can be as high as 8.2°C, and produces a maximum temperature increase in coolant B of 15.8°C. The difference in temperature registered for coolant A corresponds to temperature difference between the first and the last cell of a module. This means that a 0.17°C temperature raise is registered by coolant A for each cell. Considering a temperature coefficients of -0.06% [11], a maximum absolute difference of 0.48% electric efficiency between the first and the last cell of the module is experienced.

In any CPV receiver, the waste heat moves from the cell to the coolant through the different layers. Each layer adds a resistance to the heat path [12]: the larger the overall resistance, the lower the heat dissipated and, thus, the larger the temperature difference between the cell and the coolant. By taking into account the thermal power absorbed by the fluid and the thermal resistance of the receiver, it is possible to determine an average cell temperature of 53°C, with a maximum of 66°C. When compared to a reference cell temperature of 25°C, this translates into a daily energy loss of 6.9 kWh, corresponding to an average efficiency drop of 1.7%.

The value of delta T between the cell and the cooling fluid can be drastically decreased by reducing the number of layers below the cell. As part of a European Commission-funded project (COGEM CPVTM GA674311), Solergy designed a new type of receiver, where the cell is mounted on a ceramic based substrate, which is directly in contact with the coolant. In the new design, the thermal paste used between the substrate and the aluminum holder, where most of the thermal resistance occurs, will be removed and the heat could therefore be dissipated much more effectively, lowering the cell temperature. Based on results of the thermal model, this change would reduce the daily energy loss, compared to a 25°C condition, to 2.1 kWh, with a drop in efficiency limited to 0.5%. Preliminary outdoor measurements performed by Solergy on its test system in Formello validate the thermal model and indicate that, under the same conditions, the new receiver would lead to a reduction of 45% in the average cell temperature compared to the old receiver.

Maximizing the Power Output/Efficiency

It is of interest to determine the configuration that optimizes the power output of the system. Since the initial temperature of coolant B is constant, changing its flow rate would impact the outlet temperature of both the coolants. For example, higher flow rates reduce the temperatures of coolant B and inlet coolant A temperatures. A lower coolant A temperature would reduce the temperature of the cell and, therefore, increase the electrical efficiency of the system. On the other hand, a lower difference in temperature gained by coolant B would reduce the power output of the conventional thermal power plant.

The graph in Fig. 6 reports the variation in power loss, in cell temperature and the temperature gain of coolant B depending on the flow rate. The energy loss is obtained as sum of the loss in electrical energy output due to the temperature of the hottest cell and of the energy consumed by Pump B. The figure has been obtained by using the model developed before and considering a constant coolant A flow rate. The temperature of the cell has been calculated with an iterative function taking into account the difference between the thermal power produced and delivered by the system. Using this kind of chart, designers can optimize the flow rate of coolant B, obtaining in output the best compromise among cell temperature, temperature gain in fluid B and electrical energy yield.

CONCLUSIONS

The field performance of a commercial HCPV/T system developed by Solergy Inc. and installed at the Fiumicino airport, in Rome (Italy), has been analyzed in this study. On a clear sky day, the system has been found to operate at an average overall efficiency of 43%. It has been shown that operating efficiency can be immediately increased to 48% by adjusting the flow rate of the cooling system. The HCPV/T system works for more than 50% of the airport's peak consumption period, creating interest in its usage in a larger scale plant. The parasitic losses have been found to consume only 3.2% of the electricity produced and improvements already in development by Solergy are expected to reduce parasitic losses by 50%. In order to present an accurate report of the performance, a model has been developed to calculate the impact of the cell temperature: an average absolute loss in efficiency of 1.7% has been found because of the cell temperatures: a theoretical model estimates that these losses could be reduced to 0.5% with the new CPV receiver design developed by Solergy; preliminary outdoor measurements verify the expected improvements. The relation between the temperature of the coolants and the system efficiency has been presented and some improvements that would enhance the performance of the system have been discussed.

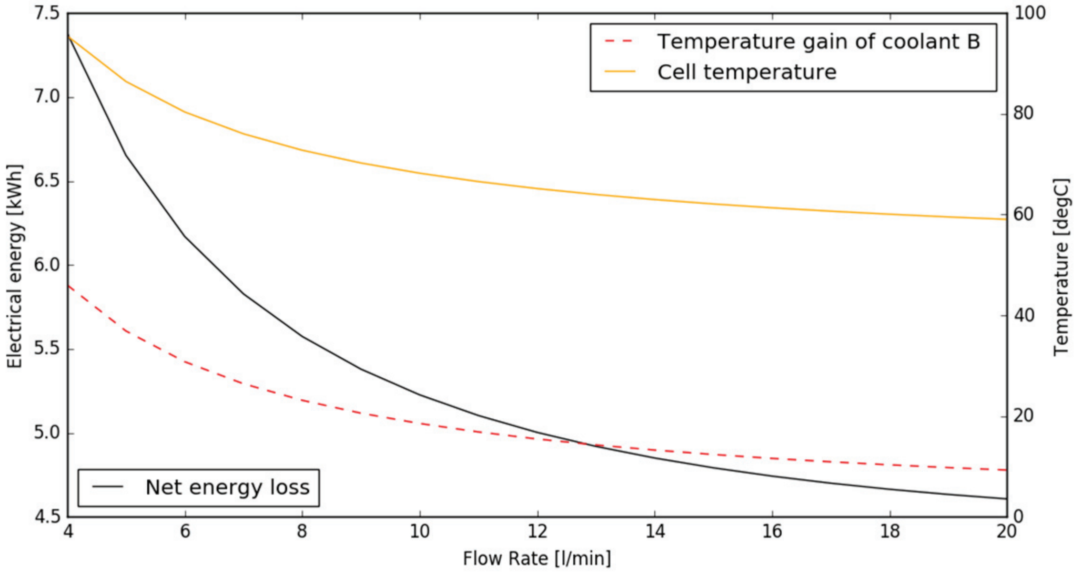

FIGURE 6. Comparing the loss in electrical efficiency, the cell temperature and the temperature difference for coolant B depending on the flow rate.

ACKNOWLEDGMENTS

Part of this work was completed under Contract N. DE-AC36-08GO28308 with the US Department of Energy and part has received funding from the European Union's Horizon 2020 research & Innovation programme under grant agreement n.674311 and contains only the Authors's view. The authors wish to thank Massimiliano Scaloni, Stefano Cerino, Luigi Briguglio and all the Solergy staff for their help with installation and operation of the data acquisition system.

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