Development, optimization, and testing of a hybrid solar panel concept with energy harvesting enhancement

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Abstract. Photovoltaics (PV) is one of the important technologies for electricity generation from renewable energies today and has an excellent environmental sustainability. It is a fast-growing market worldwide and also offers opportunities for aviation to intensify the use of renewable sources. Although the efficiency of PV systems has increased to a certain extent in recent years, a predominant part of solar radiation acting on a PV system is still lost to the environment through reflection and convection as well as heat radiation from the heated PV system. In addition, the efficiency of these systems decreases with increasing heating. Possible solutions for energy harvesting of this energy loss through thermoelectric (TE) have been investigated theoretically and in part experimentally in various cases but have not yet been transferred to larger PV systems. At the same time, cooling the PV system through thermogenerators (TEG) allows its efficiency to be increased. This contribution presents first results from investigations into the design and testing of hybrid PV/TEG systems, which aim to increase the efficiency and improve economic manufacturability of such systems. Among others, important design aspects of hybrid PV/TEG systems and integration of IoT elements (Internet of Things) are addressed and the development of an analytical model to optimise hybrid systems is presented.

1. Introduction

Renewable energies are expanding noticeably all over the world due to the energy transition. Every year, the ever-demanding growth of world population along with the necessity of sustainable energy increases the use of renewable energies [1]. From renewable energies, wind energy and solar photovoltaic (PV) have the potential to reduce the European Union's power sector dependence on natural gas by 2023 from non-European countries. The role of solar power in energy transition is getting increased and studies have shown that in 2021 worldwide 302 GW renewable power sources were installed, where solar PV alone claimed a share of 56 % [2], Figure 1. This increased use of renewable energies mainly concerns terrestrial applications but also in the field of aviation the interest on alternative energy sources is growing due to the necessity to decrease fuel demand and to develop "More Electrical Aircrafts" [3-5]. Regarding PV technology for aviation, as comprehensively summarized in [5], first investigations started in 1974 with the project Sunrise I and numerous studies in the past years were carried out focusing on manned and unmanned experimental aircrafts, on projects dealing with "High Altitude Long Endurance" and on application to airships. A remarkable example of the potential of PV in aviation was the manned circumnavigation of the earth in 17 months carried out with the Solar Impulse II airplane a few years ago [6]. Despite the numerous investigations into the use of PV in the aviation sector, studies of its application in commercial aircraft construction are rather rare. A theoretical study in [5] on the use of PV in an Airbus A340–300 and a Cessna Conquest 441 to supply the electrical demand as a supplemental power source demonstrated that systems with the PV cells on the wings can supply 45 % of the aircraft electrical demand and 100 % with additional cells on the fuselage. A comparable study on PV in a business jet also came to positive conclusions and found that a supplementary use of PV is currently at the break-even point in terms of overall aircraft performance [4]. These studies also address important aspects that need to be considered for a future implementation, such as the weight reduction of batteries needed to store energy for night-time use – which is one of the major obstacles [5] – and high values for the efficiency of the PV system and its ratio of efficiency to weight [4].

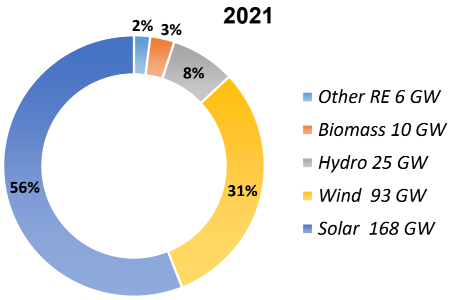

Figure 1: Net renewable power generating capacity installed in 2021 worldwide, according to [2], (RE: renewable energies).

The single crystalline, polycrystalline and amorphous silicon are the main types of PV cells currently in conventional use [7]. However, the single crystalline silicon cell – used for example in the Solar Impulse II project [4] – has higher efficiency and converts 13 - 20 % of the solar energy into electric power [8]. For all types of the above cells the remaining energy is wasted in the form of heat. This dissipated heat from the solar irradiation increases the temperature of the PV cells, thus resulting in a decrease of module efficiency with a temperature coefficient in the range of -0.23 to -0.4 %/℃ [8]. The efficiency of solar panels can be improved by adapting suitable cooling methods. Air cooling, water cooling and thermoelectric cooling are the main cooling techniques [9]. The air cooling is done either by natural flow of air or by using fans. Water spraying, floating PV (FPV) and nanofluids are the water-cooling methods and FPV is an emerging technology that cools the panel and improves their efficiency [9]. Researchers estimated that the FPV produces higher power output than the conventional land use PV because of evaporation that is taking place on the back side, which reduces the panel temperature and improves the efficiency [10-12]. Majid et al. [13] highlighted the efficiency improvement of FPV by 15.5 % in a two-hour experiment.

In order to improve the efficiency by cooling and with this lifetime and overall power production of PV panels, the integration of thermoelectric (TE) in PV in a hybrid manner is another promising solution [14]. Several researchers conducted investigations based on hybrid systems with PV integrated thermogenerators (TEG) and some were tested under laboratory conditions [14-17]. The selection of PV and TEG model plays an important role in the performance efficiency of the PV/TEG system, thus the production of power from the module can be enhanced approximately by 3 to 25 % [15] Another parameter influencing the power of hybrid PV/TEG is the internal resistance of the entire system. When the internal resistance decreases, the power produced from the PV/TEG is getting increased, possessing an inverse relationship [15]. Also, TEGs have the capability to produce power at night using dissipated heat that is stored during the day with phase change materials [16]. Zhang et al. [17] and Bjork et al. [18] performed a test with monocrystalline PV with bismuth telluride TEG and validated an increase in power of 2 - 14 % in hybrid PV/TEG systems compared to normal PV. Zhang et al. [17] conducted a test with polycrystalline PV and bismuth telluride TEG configured by a concentrator solar cell and TEG with a heat sink, and concluded the efficiency raise of 8 %. Challa et al. [9] evaluated first PV alone and then later combined the PV and TEG together by placing a copper absorber plate between PV and TEG and a heat sink placed on the other side of the TEG. This test was done through simulation providing similar standard conditions and they concluded around 6 % of increase in efficiency than the stand-alone PV panel. Furthermore, Metwally et al. [19] developed a hybrid PV/TEG model and built an active cooling system which resulted in an increase in efficiency and power generation by 4 % - 20 %. By evaluating the literature, it was analyzed that the hybrid PV/TEG has higher efficiency and better power production potential than the stand-alone PV and the efficiency of the hybrid system can be improved by adapting suitable configurations and cooling strategies.

Additionally to the cooling effect by TEGs, the implementation of TEGs into PV systems allows efficient energy harvesting. Energy harvesting is a technology in which energy is extracted from the environment and used for example to control remote sensing elements in wireless applications in the range of nW - mW [20]. Converting solar light, electromagnetic waves, magnetic fields, heat, and vibrations into electric power are the several types of energy harvesting techniques and their power densities varies from module to module [21]. The benefits of energy harvesting include the elimination of network-based energy and conventional batteries. It can minimize maintenance costs, reduce the emission of greenhouse gases, and possesses high energy efficiency in capturing, accumulating and storing small energy packets. Thermal harvesting is obtained by the use of thermal energy from the surrounding environment. The use of TEGs is one of the promising harvesting technologies, since it only requires a certain temperature difference across the thermoelectric element for producing electricity by the Seebeck effect [22]. Energy conversion efficiency of the TEG system depends on the temperature difference between the hot and cold side and the value of the figure of merit ZT of the TEG [22]. The heat source and heat sink are the two essential components coupled to TEG. Efficiencies of TEGs are usually between 5 and 10 % [23]. Moreover, TEGs are maintenance-free and have high lifetimes [24].

From this review of the literature on hybrid PV/TEG systems, it is evident that the combination of PV with thermoelectrics provides an increase in efficiency, which, as previously described, is important for an implementation of solar technology in aircrafts. Strategies to enhance performance improvement with hybrid PV/TEG systems are the focus of the work described here. However, it should be noted that the efficiency to weight ratio is not yet addressed here, but must be considered for possible implementations in the field of aviation as TEGs and cooling imply additional weight.

Scientific work on the integration of TE in PV systems has so far predominantly been carried out on a laboratory scale but have shown promising results. This paper reports on investigations that are conducted within the framework of the FAST-SMART project to develop near-series hybrid PV/TEG systems and to evaluate them under realistic conditions. Important objectives are to obtain hybrid PV/TEG systems with enhanced efficiency and lifetime compared to conventional PV, to find suitable inexpensive and economical assembly and manufacturing concepts and to use harvested energy by the TEGs for autonomous IoT-based system monitoring, control and prognoses.

2. Methodology of hybrid PV/TEG system development

The conceptual structure of the PV/TEG systems investigated consists of the following system elements: (a) silicon-based PV panels with control units, (b) TEGs that are attached to the back side of the panels and use their dissipated heat to operate the TEG's hot side, (c) cooling systems (passive or active) on the free TEG cold side to generate a sufficiently high temperature difference within the TEGs, and (d) wireless sensors and electrical control units powered by the harvested energy of the TEGs for enhanced system monitoring and control.

Development of the design of such hybrid-system can be divided into three sub-areas: (i) Dimensioning of the TEGs in such a way that they sufficiently cool the PV panel under the varying solar irradiation over the year and during the day on the one hand, and on the other hand provide sufficient energy for the operation of the connected IoT components; this involves also designing an efficient cooling system on the TEG's cold side, (ii) dimensioning of the IoT system with the focus on low energy consumption, reliable collection of essential data for monitoring (e.g. temperatures, solar irradiation, rain), efficient voltage conversion and intermediate energy storage for times with absent or low solar irradiation, and (iii) development of an assembly concept of PV panel, TEGs and cooling system suitable for production, with low heat resistance at the components' mounting points and ensuring a sufficient system lifetime.

The solutions to these individual aspects in the project are based on theoretical models and experiments. An analytical model was developed that enables the determination of the average temperatures of the PV panel and the hot and cold sides of the TEGs as well as the power output of the PV panel and the TEGs depending on the solar irradiation and the ambient conditions. It enables in particular the TEG dimensioning. For the optimisation of the hybrid PV/TEG panel design, numerical models based on the finite element method (FE) of the systems were developed, which accurately determines the temperature distribution within the panel and TEGs (Figure 2a). Missing data, such as the heat transfer between the components and the ambient air, were determined with the help of artificial neural networks and experiments. Thermomechanical coupled FE models are currently being developed to analyze thermal stresses in the joints of the hybrid system and to conduct lifetime prognoses. For initial experimental investigations, a test bench was created in which the hybrid systems can be investigated under irradiation with a metal-vapor lamp with a power of 1000 W under defined conditions and for example, different cooling strategies of the TEGs can be tested (Figure 2b,c). Hybrid systems based on PV panels with peak powers between 10 and 160 W are investigated in the project.

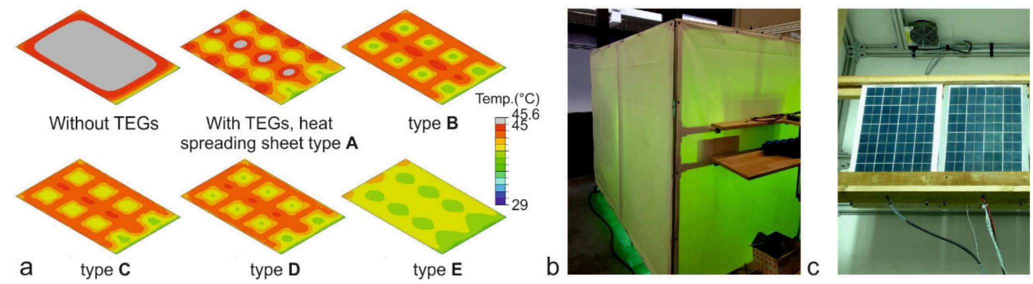

Figure 2: Investigations into hybrid PV/TEG systems, a: thermal simulations of a 30 W PV panel and different hybrid systems designs (ambient temperature: 32°C, solar irradiation 595 W/m^2), b: test bench for artificial lightening, c: hybrid systems based on 10 W PV panels on the test bench.

3. Analytical model

Figure 3 shows a schematic drawing of the hybrid system with the incoming and outgoing heat and energy flows and temperatures.

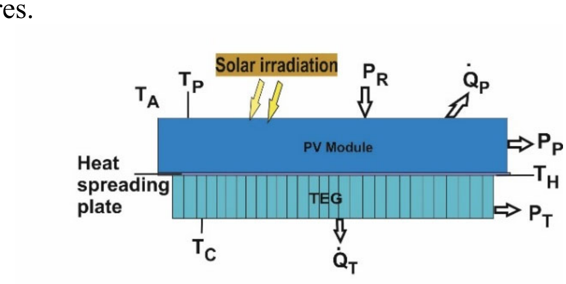

Figure 3: Schematic diagram of the hybrid PV/TEG system.

In order to determine the electrical power output from the PV panel (P_P) and from the TEGs (P_T), a simplified model was developed with the following assumptions: (a) the efficiency η_P of the PV panel depends on the panel temperature T_P via the temperature coefficient K but is independent of the radiation intensity G, (b) thermal resistances between the individual components are neglected, (c) temperature distribution on the panel is constant, (d) a heat flux loss $\dot{Q}_P$ from the front side of the panel is considered but a thermal loss from the backside of the panel other than from the TEGs is neglected. The developed model is comparable to the model presented by Zhu et al. [25] for a thermally concentrated hybrid system, but takes into account the less elaborate structure of the hybrid system considered here.

Based on the sum of energies entering and leaving the hybrid PV/TEG system with the solar irradiation P_{R} collected by the PV panel, the electric power P_{P} provided by the PV panel, the electric power P_{T} from the TEGs, the thermal loss from the Panel front side $\dot{Q}_{\mathrm{P}}$ and thermal loss from the cold side of the TEGs $\dot{Q}_{\mathrm{T}}$ it applies with the made simplifications:

$$P_{\mathrm{R}} - P_{\mathrm{P}} - P_{\mathrm{T}} - \dot{Q}_{\mathrm{P}} - \dot{Q}_{\mathrm{T}} = 0 \tag{1}$$

According to [26] the power from the panel can be described as:

$$P_{\mathrm{P}} = P_{\mathrm{R}} \cdot \eta_{\mathrm{P}} = P_{\mathrm{R}} \cdot \eta(1 + K(T_{\mathrm{P}} - 25^{o}C)) \tag{2}$$

Where η is the efficiency of the panel under standard test conditions (STC). The power produced due to the thermal energy is the product of the number n of TEGs with the square of the current I on the individual TEG and the load resistance R_{I} connected to it and can be expressed in the form:

$$P_{\mathrm{T}} = n \cdot I^2 \cdot R_{\mathrm{I}} \tag{3}$$

If radiation losses are neglected and only convection is considered, the heat emitted from the front of the PV panel to the environment can be determined from:

$$\dot{Q}_{\mathrm{P}} = \alpha_{\mathrm{P}} \cdot A_{\mathrm{P}} \cdot (T_{\mathrm{P}} - T_{\mathrm{A}}) \tag{4}$$

where α_{P} is the heat transfer coefficient at the panel front side, A_{P} the panel area and T_{A} the ambient temperature.

The total amount of heat that transfers into the TE module's hot side is developed due to the involvement of the Seebeck effect, the Fourier conduction, and Joule's heating [25]. From the incoming heat flow into the TEG, a part is converted into electrical energy and a part leaves the TEG at the cold side which is calculated as follows for the individual TEG [25]:

$$\dot{Q}_{\mathrm{C}} = N\left(\alpha T_2 \cdot I + \frac{T_1 - T_2}{R_{\mathrm{te}}} + \frac{I^2 R_{\mathrm{e}}}{2}\right) \tag{5}$$

where N is the number of legs of the individual TEG, α the temperature dependent Seebeck coefficient, R_{te} the thermal resistance of a TEG's leg pair, R_{e} its electrical resistance, and T_1, T_2 are the temperatures at the hot and cold side of TEG's legs. Assuming as mentioned above that thermal resistances between the hybrid-system components are neglected it can be written $T_1 = T_{\mathrm{P}}$ and $T_2 = T_{\mathrm{C}}$ with T_{C} as the cold side of the TEGs at which a direct heat transfer, e. g. via a radiator, to the ambient air is assumed. Considering the number n of implemented TEGs, it applies than:

$$\dot{Q}_{\mathrm{T}} = n \cdot \dot{Q}_{\mathrm{C}} = n \cdot N\left(\alpha T_{\mathrm{C}} \cdot I + \frac{T_{\mathrm{P}} - T_{\mathrm{C}}}{R_{\mathrm{te}}} + \frac{I^2 R_{\mathrm{e}}}{2}\right) = \alpha_{\mathrm{T}} A_{\mathrm{T}} (T_{\mathrm{C}} - T_{\mathrm{A}}) \tag{6}$$

where α_{T} is the heat transfer coefficient at the TEG cold side and A_{T} the area of n TEGs from where heat is transfered to the environment.

The maximum power output for a TEG is achieved when the load resistance R_{I} connected to the TEG corresponds to its internal resistance $N{\cdot}R_{\mathrm{e}}$. It is therefore assumed for the current I [25]:

$$I = \alpha \frac{(T_1 - T_{2)}}{2R_e} = \alpha \frac{(T_{\mathrm{P}} - T_{\mathrm{C})}}{2R_{\mathrm{e}}} \tag{7}$$

The electrical and thermal resistance of a TEG leg pair can be calculated by $R_{\mathrm{e}} = \rho l / A$ and $R_{\mathrm{te}} = l / (\lambda A)$ where A is the cross-sectional area of the individual TEG leg and ρ, and λ are the electrical and thermal resistivity and l its length.

Equations (1-7) allow us to determine the power output of a PV/TEG system under the simplifications made as a function of the implemented TEGs and their number and depending on environmental variables.

For the example of a hybrid system, developed within the frame of FAST-SMART, Table 1 shows an example of a comparison of experimentally determined data with theoretical data calculated with the described model. For the calculation, the temperature dependent values of the TEGs for α, R_e and R_{te} were determined based on the data sheets provided by the TEG manufacturer. The hybrid PV/TEG system was based on a monocrystalline PV panel with a peak power of 30 W (type GA-F030E, Bosswerk) and eight TEGs with a matching load output of 15.6 W (type GM200-127-28-12, European Thermodynamics). The cold side of the TEGs was equipped with radiators which could be used as passive cooling and as active cooling with fans. The experiments were conducted in the test bench described above where light irradiation, all relevant temperatures and currents and voltages for power determination were measured.

Table 1: Comparison of experimental and theoretical data as an example (G = 200 W/m^2, T_A = 21.26 °C, α_P = 2 W/(m^{2}K), α_T = 500 W/(m^{2}K)).

Parameters	Experiment	Model
Panel temperature T_P (°C)	25.43	25.07
TEGs cold side T_C (°C)	22.11	22.95
Power output (W)	4.07	4.08

Despite the simplifications made for the analytical model, it shows a comparatively good prediction of the experimental values with deviations below about 3.8 % in the considered example.

Further theoretical analyses based on the developed model were carried out to determine the influence of number n of TEGs on a monocrystalline panel with larger size and a peak power of 80 W (type sun plus 80, phaesun), applying the above mentioned TEGs. The number of TEGs attached to the PV panel defines the achievable thermal effect on the panel and the overall power output of the system. The manufacturing costs, weight and the effect of sustainability are other factors that should also be considered when determining the number of TEGs. For the example of a positioning of the hybrid system in North Rhine-Westphalia in Germany and average values for solar radiation and daytime temperatures in summer, Figure 4 shows the development of the panel temperature as a function of the number of TEGs, as well as the electrical power output of the panel and the TEGs, determined with the analytical model described above.

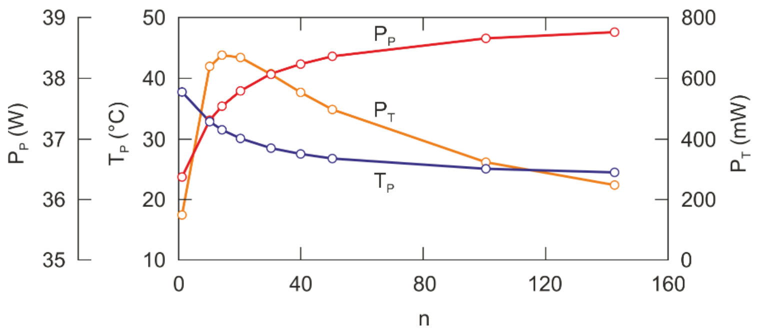

Figure 4: Example of power outputs P_P and P_T and temperature of the PV module at a hybrid PV/TEG panel (based on a 80 W PV panel) as a function of the number n of TEGs (T_A = 22.7 °C, G = 483 W/m^2).

Based on these results it is understood that with the increase in the number of TEGs, the temperature on the PV module decreases gradually. This is because with an increase in the number of TEGs more heat is dissipated into the surrounding environment. Since this effectively lowers the maximum temperature of the entire system it results in a higher energy power production from the PV panel with increasing *n* as depicted in Figure 4. The power output of the TEGs initially increases as their number increases and then falls continuously after a maximum at about *n* = 14 for this example. This happens because TEGs generates electricity based on the temperature difference between the hot and cold side but after a certain range of increase in *n* the generated temperature at the hot side of TEGs decreases and results in a decrease in power output.

4. Conclusion

This paper reports on research into the development of IoT-assisted hybrid PV/TEG systems which is of particular interest in the context of the growing demand for renewable energy, and an insight into the objectives, structure of the work and methods used is given. Furthermore, the development of an analytical model for the design of hybrid PV/TEG systems is presented that provides a very good prediction of achievable performances of the investigated hybrid systems. One important advantage of hybrid PV/TEG systems is the production of additional electricity with energy harvesting TEG modules by the utilization of waste heat from the PV module which at the same time increases the PV module performance by reducing its temperature. The theoretical and experimental investigations carried out until now demonstrate the potential of this hybrid technology Next steps will therefore deal with the testing of larger hybrid prototypes and driving forward the development and investigations of near-series concepts and integration of IoT elements contributing to increasing the benefits. The possibility of increasing efficiency of PV systems is particularly important for aviation, which is currently also exploring practicable and economical ways to use renewable energies and for which notable potentials through PV can be identified.

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