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Article

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Thermal and electrical performance assessment of a solar polygeneration system

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Abstract

In this paper, a reliable and cost-effective polygeneration system for an existing test building, able to provide electricity, cooling and heating needs is presented, modelled and assessed. The system relies on solar energy as the primary source (PV and solar thermal collectors). Building cooling demand is achieved with a variable geometry ejector heat pump. To reduce the mismatches between generation and consumption, different types of storage are included (electrical and thermal). A system prototype is under development and will be installed as a demonstration site in Portugal.

To assess the test building energy needs, the electricity consumption of all consumers was measured. For the thermal energy demand a numerical model using TRNSYS software was developed. The building thermal performance was validated using experimental data. The numerical model also includes the solar field, thermal energy storage and ejector cycle. To model and simulate yearly electricity production PVSyst software was used.

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Keywords: PV electricity; Polygeneration; PVSyst; Solar thermal; Test-building; TRNSYS

1. Introduction

Buildings are responsible for a large portion of the energy consumption and harmful emissions to the environment. To change this situation, the European Performance of Buildings Directive requires new buildings to be nearly Zero Energy Buildings [1]. To achieve this goal energy saving measures combined with large use of renewables on-site must be applied.

A polygeneration system, also referred to as CCHP (combined cooling, heating and power), is a type of system where the production of power, heating and cooling comes from the same source, resulting in energy savings and environmental benefits over conventional generation systems [2]. The evaluated system is a reliable and cost-effective polygeneration system for an existing test building (SOLAR-TDF: Solar Test and Demonstration Facility

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[3], able to provide electricity, cooling and heating needs. The system uses only solar energy as main source, through photovoltaic (PV) and solar thermal (ST) collectors. It also includes different types of storage (electrical and thermal).

The assessment of the thermal energy demand was carried out using a dynamic mathematical model, developed with a commercial software, TRNSYS [4]. To model and simulate yearly electricity production from the solar panels, the PVsyst commercial software [5] was applied. To assure the numerical building model provides acceptable accuracy, results were validated with experimental data. The developed dynamic models were used to assess the year-round thermal and electrical performance of the test facility. Results include the daily, monthly and yearly thermal and electrical energy consumption of the test facility, as well as peak electrical power, peak cooling and peak heating loads.

2. Models and methods

2.1. Year-round thermal energy consumption assessment

2.1.1. Experimental data collection for model validation

To assess the thermal energy consumption of the SOLAR-TDF, local climatic conditions such as ambient temperature, solar radiation intensity, relative humidity, etc., should be measured. Also, assuming natural ventilation and no active heating or cooling inside the test building, the indoor temperature and infiltration rate of building should be evaluated. Experimental measurements should be done for a one-year period, which is quite long, and therefore it is more reasonable to use a dynamic numerical simulation, as in this case using a TRNSYS model.

To ensure the accuracy of the simulation results, these should be validated by experimental measurements. Therefore, local climatic conditions and indoor temperature were monitored for a period of about one month, from 24th of August to 19th of September. Data logging was done with intervals of 15 min.

2.1.2. Development of numerical TRNSYS model

A numerical model using TRNSYS was used to determine the thermal energy demand of the SOLAR-TDF. The building model was completely defined specifying the composition of the walls, their thermos-physical properties, their orientation and size, indoor gains, infiltration rate, etc. Some of the physical properties (e.g. thermal conductivity, density and specific heat capacity) of the building envelope were measured and some others were estimated (e.g. optical properties). Besides the building model, other components were also included in the TRNSYS model such as the solar field (SF), thermal energy storage (TES), ejector cooling cycle (ECC), subjected to known meteorological conditions and control strategy, as shown in Fig. 1.

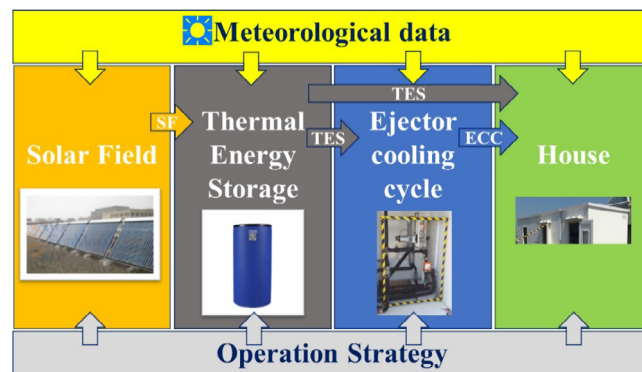


Fig. 1. Model components for the thermal load simulations.

The SOLAR-TDF is located on the rooftop of a building at the University of Porto (Faculty of Engineering), Portugal. For the meteorological data, a Typical Meteorological Year (TMY) for Porto from Meteonorm software was used. The annual global horizontal radiation is about 1773 kWh/m² with an average ambient temperature of 14.5 °C.

Four evacuated tube solar collectors (ETC) are connected in series to build the solar field. The total net collecting area is about 13 m². The efficiency curve was provided by the manufacturer as Eq. (1).

$$\eta_{collector} = 0.832 - 1.14 \frac{T - T_{amb.}}{I} - 0.0141 \left(\frac{T - T_{amb.}}{I} \right)^2 \quad (1)$$

where I , \bar{T} and T_{amb} are incident solar radiation, mean collector temperature and ambient temperature, respectively. The TES is modelled considering a water-filled sensible energy storage tank, subjected to thermal stratification by assuming the tank consists of 12 fully mixed equal volume segments. Moreover, constant loss coefficients were assumed for each segment and heat transfer between adjacent nodes is done by convection. The tank was oversized (5 m³) to store the maximum possible thermal energy produced by the solar field. Modelling of the control strategy to circulate water between SF and TES is done by maintaining a 3 °C temperature difference between solar field and tank outlet.

Based on previous experiments [3], the average COP of the ejector cycle was measured to be 0.28. In this paper modelling was simplified and a more conservative constant COP of 0.25 was used. Therefore, the thermal consumption of the cooling cycle is four times the thermal production which is stored in TES.

In addition, a heater/cooler (fan-coil) was modelled inside the building to increase or decrease the room temperature when it deviates from the set-point (comfort) temperature. The heating and cooling rates associated with the heater/cooler, were previously measured for the SOLAR-TDF, with 2.6 kW_{th} for heating and 1.6 kW_{th} for cooling. The heater only operates from January until the end of May and from October until the end of the year (heating season), when the indoor temperature is lower than 22 °C; the cooler only operates from June until the end of September (cooling season), when the indoor temperature is higher than 26 °C. This operating strategy for the heater/cooler device does not guarantee that during the whole year the indoor temperature will remain in the comfort zone (22–26 °C). In particular, the room is not going to be heated and cooled during the same day.

To validate the numerical model, simulations were performed with a time interval of 15 min. With respect to simulations throughout the year, the time interval was considered as 30 s.

2.2. Year-round electrical energy consumption assessment

2.2.1. Mathematical model for the electricity production

TRNSYS has the capability to simulate PV electrical systems. However, PVsyst software is a widely used tool for modelling photovoltaic systems. PV mono-crystalline modules with a surface area of 1.62 m² and nominal pick power of 265 W_p were modelled in PVsyst. The same methodology as with TES was applied to model the electricity energy storage, which means that energy (electricity) generated by PV modules, is stored in a large energy storage (electric grid).

2.2.2. Electricity consumption assessment

To assess the electrical consumption of the SOLAR-TDF, first the consumption of each electrical device should be measured. It should be noted that for single phase consumers, this was done by measuring power, current and voltage using an ordinary multi-metre. Regarding three phase consumers, apparent, active and reactive power in conjunction with the power factor were measured by a MICROVIP 3 PLUS energy analyser. The total power consumption measured was 1.1 kW_{el} and the largest consumption (more than 50%) was related to the heat dissipation fan-coil which is used to protect the solar field and cooling the condenser during cooling operation. It is noteworthy to mention that all the electrical consumers do not operate at the same time and there is an operational period for each one. For example, computer and data-logger work in full-time, while the dissipation fan-coil only operates in short periods when the heat produced is higher than what could be stored in the TES. To simplify modelling of electrical consumptions, the consumers are grouped according to their operational function: data acquisition with 0.11 kW_{el} consumption, solar field with 0.18 kW_{el} consumption, dissipation with 0.75 kW_{el} consumption, cooling with 0.36 kW_{el} consumption and heating with 0.09 kW_{el} consumption.

3. Results and discussion

3.1. Model validation

Simulations were carried out with measured meteorological data as input. Thereafter, for validation, the simulated indoor temperature was compared to the measured indoor temperature. The resulting comparison for 26 days is illustrated in Fig. 2. After tuning the model by changing some of the estimated building properties (gains, solar absorption of the roof, emission coefficient of walls, shading considerations in the north and east walls, the convective heat transfer coefficient of the ground and fraction of the total solar radiation that strikes the surfaces), a very good agreement between simulation and measurements was obtained. The maximum temperature difference was 4.2 °C on 17th and 18th of September and the root mean square error was about 1.1 °C.

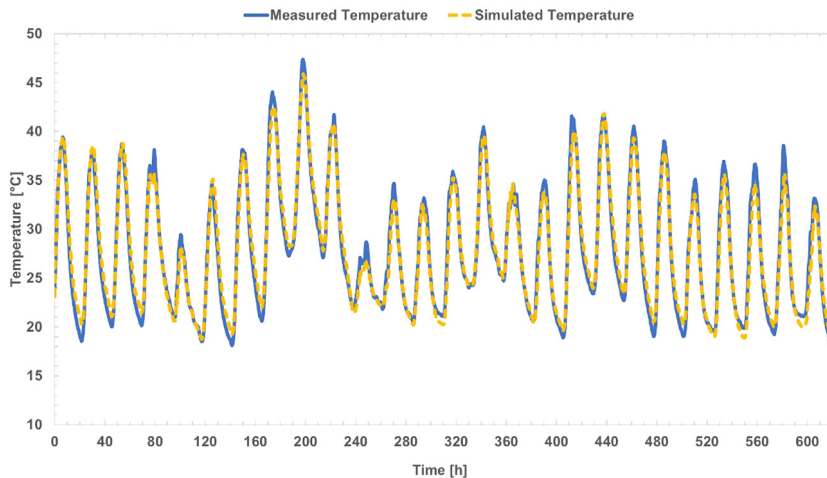


Fig. 2. Comparison between measured and simulated indoor temperature for 26 days.

3.2. Yearly thermal performance

Fig. 3 shows the thermal energy production from the solar collectors and the thermal energy consumption (heat demand) of the test facility for each month. It can be concluded that the existing solar collector field always produces thermal energy that satisfies the thermal demand for heating or cooling during the whole year. The maximum heat consumption occurs in the cooling season in July, when thermal energy production by the solar collectors and

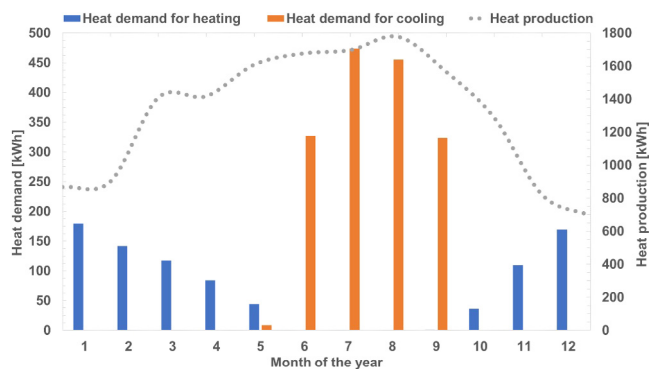


Fig. 3. Monthly thermal energy consumption and production.

thermal energy consumption of the cooling cycle generator is similar (~ 450 kWh_{th}). For the rest of the year, monthly production is higher than monthly consumption. The minimum energy consumption occurs in May and October (mid-season) note that the energy production is generally high compared to the energy demand. The largest difference between production and consumption occurs in May and October.

Based on the simulation, the total heat production during the year was 15.7 MWh_{th} while the total heat consumption was 2.5 MWh_{th} (including 1.6 MWh_{th} for cooling and 0.9 MWh_{th} for heating). There is a large difference between heat production and consumption, due to system design and test building/weather conditions. It must be noted that the polygeneration system prototype has the capacity to provide heating/cooling for a larger/real building, as required in practical applications. The solar collectors were selected to satisfy the heat demand for the cooling cycle capacity (1.6 kW) and with the small test building used there are large periods with no requirements for cooling or heating. In a real building the excess energy can also be used for domestic hot water or swimming pool heating.

Note that it is possible to have a lower daily energy production compared to daily consumption, while the monthly production is higher than the monthly consumption. An example of this behaviour is illustrated in Fig. 4, where the daily difference between the thermal energy production and consumption is presented during the year. The negative values are days with lower energy production in comparison to consumption. The highest thermal energy deficit was found on 14th of February (9 kWh_{th}) and on 15th of February (10 kWh_{th}). The reason is that the daily heat production is negligible (0.4–1.2 kWh_{th}) to maintain the thermal comfort and the TES unit is needed. The TES can be charged during 13th of February (excess thermal energy of 36.8 kWh_{th}) and discharged when the production is reduced.

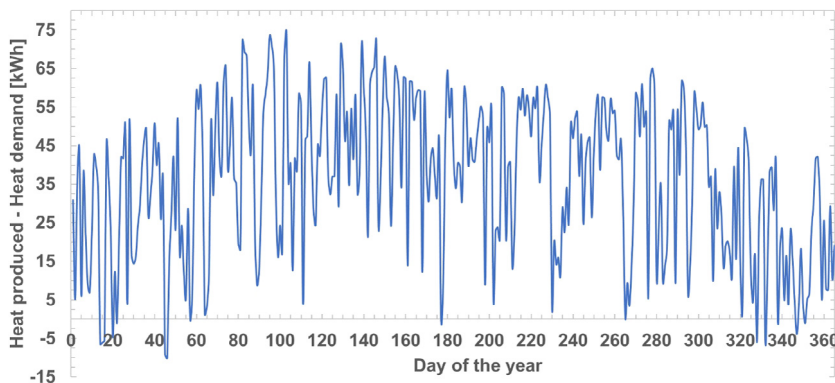


Fig. 4. Daily difference between heat produced by the solar collectors and consumed for indoor temperature control.

3.3. Yearly electrical performance

Simulations were done considering two cases: 7 and 8 PV modules arranged in series, with south orientation (azimuth = 0) and a tilt of 35° from the horizontal. The reason for this tilt is that the incident solar radiation with this angle is maximum during the cooling season, which is the period with higher electrical needs (cooling mode operation). Therefore, the maximum annual electricity production is achievable. In Fig. 5, the monthly electricity production and consumption during the year is illustrated. Similar to the thermal energy monthly performance, electrical monthly production always satisfies the electrical monthly consumption. The maximum production and consumption occur in summer.

In general, the simulated annual electricity production was 3 MWh_{el} (7 PV modules) and 3.3 MWh_{el} (8 PV modules). In addition, the electricity consumption was simulated to be about 1.9 MWh_{el}. The annual electrical energy consumption includes 51% for continuously operation of the data-acquisition system, 33% for the solar field, 10% for dissipation of the excess heat, 4% directly for cooling and 2% directly for heating.

As with the thermal energy performance analysis, it is important to verify the electrical energy production and consumption on a daily basis. In Fig. 6, it is shown that although monthly electrical demand was satisfied,

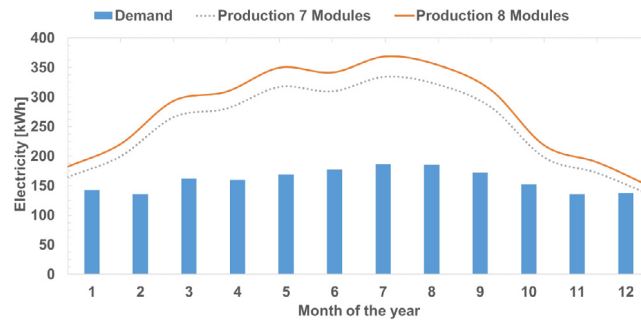


Fig. 5. Monthly electrical energy consumption and production.

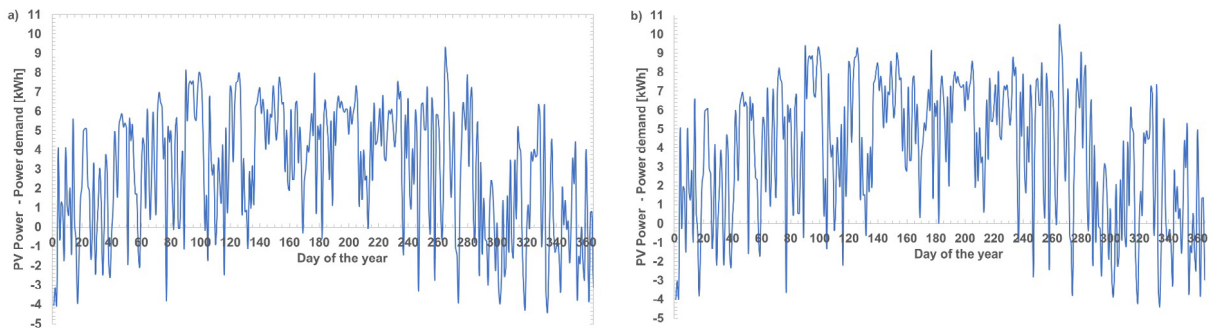


Fig. 6. Daily difference between electricity generation and demand for PV module number of: (a) 7 and (b) 8.

there were days with deficit of energy production compared to consumption (represented with a negative number). The maximum energy deficit is achieved on 30th of November (about 4.4 kWh_{el}) due to low daily electricity production (below 0.5 kWh_{el}). Therefore, it is necessary to consider an electrical energy storage unit. Considering consecutive days from the 1st to the 3rd of January with energy deficit, a value of about 11 kWh_{el} needs to be stored. Additionally, PV and electrical storage (batteries) must be capable of overcoming the instantaneous power peaks. The highest peak occurs in Summer (~0.8 kWh_e) because of lower solar radiation at the end of the day and higher demand due to high cooling load of the test building (approximately all electrical devices are operating at the same time).

4. Conclusion

A polygeneration system prototype, driven by solar energy and able to provide electricity, cooling and heating needs was modelled and assessed, when coupled to an existing test building in Porto. It includes thermal and electrical energy storage.

For the thermal energy performance, a numerical model using TRNSYS software was developed. The model was validated using experimental data. To model and simulate yearly electricity production PVSyst software was used.

Regarding thermal energy, during the whole year the energy produced is six times higher than the test building energy needs (15.7 MW_{th} of heat production and 2.5 MW_{th} of heat consumed). On a daily basis, there are a few days with energy deficit, which highlight the requirement of a TES for maintaining thermal comfort. This means that when applied to a real building, the polygeneration prototype has the capacity to supply a larger heating and cooling demand. This will be evaluated in a future work.

Regarding electrical energy consumption, it was observed that energy production for 7 and 8 PV modules was 1.6 and 1.7 times the energy demand, respectively. As with thermal energy, on daily basis there are days with energy deficit, which highlights the requirement of electrical energy storage to assure independence from the electrical grid.

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