POLYSOL – Thermal and electrical performance assessment of a cost-effective polygeneration system

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Abstract. 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 [1] requires new buildings to be nearly Zero Energy Buildings. To achieve this goal, energy saving measures combined with large use of renewables on-site must be applied. 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 heat and cooling demand is achieved with a variable geometry ejector heat pump. To reduce the mismatches between generation and consumption, it includes different types of storage (electrical and thermal). For the test building energy needs assessment, the electricity consumption of all test building consumers was measured. Thermal energy demand evaluation required the development of a dynamic numerical model using TRNSYS software. The building thermal performance was validated using experimental data. The numerical model also includes the solar field, thermal energy storage, ejector cycle subjected to know meteorological conditions and operation control. To model and simulate yearly electricity production PVSyst commercial software was applied. Regarding the thermal energy, it was found that on a yearly basis the energy supplied by the thermal collectors about six times the demand. Nevertheless, on the hourly and daily levels, there are thermal energy shortages, due to the lack of solar radiation or mismatch between production and demand. Regarding the electric energy consumption, the potential electric energy production is about 1.6 times the demand. Like for the thermal energy, on the hourly and daily levels, there are energy deficits mostly in winter, for which an electrical energy storage unit will be used. Additionally, the highest peak occurs in summer because of low solar radiation at the end of the day and high demand due to the high cooling load of the test room.

1. Introduction

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

In this paper, a reliable and cost-effective polygeneration system for an existing test building (SOLAR-TDF: Solar Test and Demonstration Facility [2]), 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 heat and cooling demand is achieved with a variable geometry ejector (VGE) heat pump. To reduce the mismatches between generation and consumption, it includes different types of storage (electrical and thermal). However, the integration of distinct renewable and storage systems with a variable daily and yearly energy demand is complex [3]. Therefore, a system prototype is under development and will be installed as a demonstration in Portugal.

The building energy assessment was carried out with a developed numerical model by the combination of two commercial software: TRNSYS [4] and PVsyst [5]. The model was validated using experimental test results. Results include daily, monthly and yearly thermal and electrical energy consumption and production of the test facility, as well as peak electrical power, peak cooling and peak heating loads.

2. Research Methodology

The SOLAR-TDF is constituted by: a solar collector field; the VGE heat pump; the thermal energy distribution (cooling and heating); air-conditioned space; and an equipment room, as shown in Figure 1. The solar field is composed by 17m² of evacuated tube solar collectors, providing heat to drive the VGE heat pump, which is installed in the equipment room. The VGE heat pump permits to accommodate both building heating and cooling demand. A dissipation fan coil unit is used to protect the collector field or for cooling the VGE heat pump during the cooling operation.

The assessment of the SOLAR-TDF energy needs, both electrical and thermal, was carried out through experimental and simulation approaches. Initially, the electricity consumption of each electric device was measured (section 2.1). The assessment of the thermal energy demand required the use of a dynamic mathematical model, developed using a commercial software TRNSYS (Section 2.3). To assure the numerical building model provides acceptable accuracy, results were validated (Section 3) with experimental data (Section 2.2). To model and simulate yearly electricity production by the solar panels, the PVsyst commercial software was applied (Section 2.4).

2.1. Electricity consumption assessment

The consumption of each electric device of the SOLAR-TDF determined through power, current and voltage measurements of the single-phase devices; and apparent/reactive power and power factor measurements for the three-phase consumers, using MICROVIP 3 PLUS energy analyser.

The total power consumption of the SOLAR-TDF is about 1.1 kWel, with more than 50% due to the heat dissipation fan coil unit, used for the protection of the collector field or eventually for cooling the condenser during cooling operation. Nevertheless, during regular operation, the electrical devices do not work simultaneously. For simulation purposes, the electric devices of the test facility were grouped
according to their principal function: data acquisition, solar field, dissipation fan coil unit, cooling and heating (see Figure 2).

Figure 2. Electrical consumption (kW\textsubscript{e}) by operation mode.

2.2. Experimental data collection for model validation
Experimental determination of the thermal energy demand of the SOLAR-TDF requires detailed measurement of the local climatic conditions (ambient temperature, solar radiation, wind speed and direction, etc.); indoor temperature and infiltration rate measurement for a one-year period. Therefore, it is common practice to use a dynamic mathematical model to carry out this task. In this case, the model was developed using a commercial software TRNSYS.

In order to assure that the numerical building model provides acceptable accuracy during the simulations, it is crucial to validate the results with experimental data. For this purpose, the local climatic data was measured (i.e. global horizontal solar radiation, relative humidity and ambient temperature) and the indoor temperature (5 thermocouples) was monitored without active air conditioning during an approximately one-month period from 24\textsuperscript{th} of August to 19\textsuperscript{th} of September. Data logging was performed in 15 min time intervals.

2.3. Development of the numerical TRNSYS model
The dynamic model was developed using TRNSYS Simulation Studio, whilst the test building was modelled using TRNBuild. In TRNBuild the building model was completely defined specifying the composition of the walls, their thermo-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, 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 Figure 3. These other components were not used during the building model validation phase.

Figure 3. Model components for the thermal load simulations.
For the metrological data, a Typical Metrological Year (TMY) for Porto city from Meteonorm software was used. The annual global horizontal radiation is about 1773 kWh/m\(^2\) with an average ambient temperature of 14.5ºC. The solar field is composed by the four BAXI-AR-30 collectors in series, with a net absorber area of about 13 m\(^2\). The efficiency curve was defined according to the manufacturer’s specifications as:

\[
\eta_{\text{collector}} = 0.832 - 1.14 \frac{\bar{T} - T_{\text{amb}}}{I} - 0.014 \left( \frac{\bar{T} - T_{\text{amb}}}{I} \right)^2
\]

Where \(I, \bar{T}, T_{\text{amb}}\) represent incident irradiation, mean collector temperature and ambient temperature, respectively. The TES tank was modelled considering water as heat transfer fluid. In order to address stratification, the tank was subdivided into 12 fully-mixed equal volume segments. Additionally, constant losses were assumed for each segment, considering a typical 10 mm thick polyurethane insulation layer (thermal conductivity of 0.03 W/m.K). The tank volume applied was highly over-sized with 5 m\(^3\) capacity, to avoid energy dissipation during high solar radiation periods. The control strategy between the solar energy and TES was achieved using an on/off differential controller to preserve a 3ºC temperature difference between the SF and TES tank outlets.

A simplified and conservative methodology was used for the ECC based on the operational experience [2]. A fixed Coefficient of Performance (COP) of 0.25 was set, i.e. the cooling cycle thermal demand is four times the thermal production. Within the test room, a heating and a cooling device were modelled to elevate or reduce the room temperature, respectively. The heat is added or removed from a flow stream at a specified rate (2.65 kW\(_h\) for heating and 1.6 kW\(_h\) for cooling), whenever the room temperature is lower than 22ºC (heating) or higher than 26ºC (cooling). A 15-minute time-step was used for the validation of the model, whilst a 30-seconds time-step was adopted for the year-around simulations due to the higher complexity of the system. As control strategy, separate heating and cooling seasons were defined (i.e. no need for heating and cooling during the same day). The heating season was set from October to May and the cooling season from June to September. Although this strategy does not permit to always achieve an indoor temperature within the predefined limits (22ºC to 26ºC), it was considered to be unrealistic to heat and cool the building during the same day.

Additionally, it was found that when the indoor temperature rises above 26ºC during the heating season, the ambient temperature remains relatively low and thus free cooling is a valid option for assuring thermal comfort of the occupants. The electricity consumption was also simulated using the TRNSYS model. Based on the control signal for the pumps, fan coils, etc., the operation of the electric devices can be predicted for each time step. The corresponding electricity consumption was calculated according to the measured data (see Section 2.1).

2.4. Mathematical model for the electricity generation by the PV modules
To model and simulate yearly electricity production by the solar panels, the PVsyst commercial software was used. Although TRNSYS has some capabilities to simulate PV electricity generation, PVsyst is a more reliable tool and a reference application for photovoltaic system simulations with extensive component model libraries. For the simulations, the monocrystalline modules with reference 04TA_16410989 by ONYX were considered. In order to assess the full production potential of the PV solar field, a similar approach was followed as in the case of the TES system. Namely that the generation of the panels was evaluated using a large capacity energy storage, in this case, the electric grid.

3. Model Validation
For model validation purpose, simulations were carried with the developed building model, without active heating and cooling. The measured metrological data were used as boundary conditions, and the simulated indoor temperature results were compared to the measured ones, calculated as the average of the five thermocouple readings. During these simulations, some of the estimated building properties were changed so that the deviation between simulated and measured temperatures were reduced. A
comparison between the measured and simulated indoor temperatures is shown in Figure 4 for about 26 consecutive days. It is noticeable, that after tuning of the model, a very good agreement between simulated and measured data was obtained. The maximum temperature difference found was 4.2ºC, and the root-mean-square error is about 1.1ºC.

4. Results and discussion

4.1. Yearly thermal performance

Figure 5 shows the monthly thermal energy consumption and solar heat production of the test facility. It can be seen that the thermal demand is always satisfied by the production by the existing solar collectors. The highest heat demand occurs in the summer, as a result of the increased cooling load and in agreement to the generation. This clearly shows the benefit of using solar energy for space cooling. The maximum heat demand is in July when there is a match between the heat supplied by the solar collector and the heat consumption the generator of the cooling cycle (~450 kWh). For the rest of the year, monthly production is considerably higher than consumption.

On a yearly basis, a total heat production of about 15.7 MWh was simulated. The annual heat consumption is about 2.5 MWh, with about 1.6 MWh for cooling and 0.9 MWh for heating (see Figure 6). This significant mismatch between heat production and consumption is mostly because the SOLAR-TDF was designed to meet the space cooling need of the test room, and also there are extensive periods when nor heating nor cooling is needed to maintain indoor comfort. In a real application, overall solar energy efficiency can be improved by integrating the developed system with e.g. domestic hot water production or swimming pool heating.

Figure 5. Monthly thermal energy consumption and production.

Figure 6. Annual heat consumption for heating and cooling.
It should be noted that even though thermal energy production is considerably higher in the SOLAR-TDF on the monthly and annual basis, there might be shortages on the hourly and daily level, due to the lack of solar radiation or temporal mismatch between production and demand. This effect is explained in Figure 7, where the daily difference between heat production and demand is plotted for the whole year. Negative values indicated a lack of useful solar heat. The highest thermal energy deficit was found for the 15th of February, with about 10 kWhth. Additionally, in the previous day (14th of February) a deficit of about 9 kWhth was also obtained. In this set of two critical days, solar heat production is almost negligible (0.4 to 1.2 kWhth). Thermal comfort can only be maintained with the implementation of a TES unit. TES can be charged with the excess thermal energy during the previous day (36.8 kWhth on the 13th of February), and discharged when the production is reduced. With a TES unit of about 20 kWhth, the thermal comfort in the test room can be assured during the entire year.

4.2. Yearly electrical performance
Two cases were assessed, one with 7 and another one with 8 modules in series, with a yearly fixed tilt angle of 35º and south orientation. The tilt angle was defined to achieve maximum annual generation. Figure 8 shows the monthly electricity consumption and production of the test facility. The electricity demand is always satisfied by the production, with the highest consumption and production occurring in the summer months. On a yearly basis, a total electricity production between 3 MWhel (7 modules) and 3.3 MWhel (8 modules) was simulated. The annual electricity consumption is about 1.9 MWhel, with more than 50% related to the continuously operating data acquisition system (see Figure 9). The annual solar electric energy efficiency is about 60%.

Figure 7. Daily difference between heat produced by the solar collector and consumed for indoor temperature control.

Figure 8. Monthly electrical energy consumption and production.

Figure 9. Annual consumption fraction of consumers groups.
The solar collector field is found to be responsible for more than 33% of annual energy consumption with the already installed solar field. Whilst the dissipation of the excess heat consumes the highest electric power (see section 2.1), it represents only about 10% of the total electrical energy consumption. It is worth noting that only about 6% of the electricity consumption is directly for heating and cooling, emphasising one of the main advantages of this thermally-driven HVAC solution.

Again, although electrical energy demand is assured by the PV modules on the yearly and monthly basis, there are periods of the year with electrical energy deficits, occurring mostly during the winter (see Figure 10) due to the time mismatch between demand and production. The maximum electrical energy deficit, about 4.4 kWh$_{el}$, was found for 30th of November and related to a rather low daily PV energy production (bellow 0.5 kWh$_{el}$). To assure the test facility’s grid independence, an electrical storage unit will be implemented. Considering the cumulative data, i.e. consecutive days with a negative electrical energy balance, a maximum value of about 11 kWh$_{el}$ was identified, corresponding to three consecutive days of energy scarcity from 1st to 3rd of January.

The power subsystem, PV and electrical battery also must handle instantaneous power peaks. Figure 11 shows the hourly electrical energy balance for the PV arrays of 7 modules. On the hourly basis, the highest peak occurs in summer (~0.8 kW$_{el}$), as a consequence of low solar radiation at the end of the day (see Figure 11-detail) and high demand due the high cooling load of the test room (almost all electric devices are operational at the same time).

5. Conclusions
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. Numerical and experimental works have been carried out with the principal objective of identifying both thermal and electric energy consumption of the SOLAR-TDF throughout the year. Additionally, this energy demand was compared to the production potential of the existing solar collector field and the to be installed PV array.

Regarding the thermal energy, it was found that on a yearly basis the energy supplied by the thermal collectors (15.7 MWh$_{th}$) is about six times the demand, with about 64% of the total demand required for cooling. On the hourly and daily levels, there are thermal energy shortages, due to the lack of solar
radiation or mismatch between production and demand. The highest cumulative thermal energy deficit (19 kWhth) was found for the 14th and 15th of February. During this period, thermal comfort can be maintained with the implementation of a TES unit, using the excess thermal energy during the previous day (36.8 kWhth on the 13th of February).

Regarding the electric energy consumption, the data indicated that the annual demand is about 1.9 MWhel, with more than 80% of the total demand required for the data logging and the solar collector field. Regarding the potential electric energy production, it was found that the electricity produced with 7 and 8 PV modules (1.6 m²) is about 1.6/1.7 times the demand, respectively. Whilst the maximum annual generation is attained for a 35º tilt angle, tilt angles between 25º and 55º should be assessed, i.e. maximum electrical energy production for winter and summer season respectively, in order to find the optimum layout to reduce the divergence between production and demand.

Like for the thermal energy, on the hourly and daily levels, there are energy deficits, mostly in winter, due to the lack of solar radiation or mismatch between production and demand. The maximum cumulative electrical energy deficit (~11 kWhel) was found for three consecutive days of energy scarcity from 1st to 3rd of January. To assure the test facility’s grid independence, an electrical storage unit will be implemented.

On the hourly basis, the highest peak occurs in summer (~0.8 kWel), as a consequence of low solar radiation at the end of the day and high demand due to the high cooling load of the test room. The power subsystem, PV and electrical battery also must handle these instantaneous power peaks.

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**References**

[1] The Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings. Official J Eur Union 2010 53

[2] Varga S, Oliveira A C, Palmero-Marrero A and Vrba J, 2017 Renew Energ. 109 83-92

[3] Lu Y, Wang S, Shan K, 2015 Appl Energ. 155 463-77

[4] University of Wisconsin—Madison, Solar Energy Laboratory, 1975 TRNSYS, a Transient Simulation Program Madison, Wis

[5] Mermoud A, 2018 PVSYST: Software for the study and simulation of Photovoltaic systems Ed. 6.7.8. University of Geneva

Pereira PR, Varga S, Oliveira A C and Soares J, 2015, Front. Mech. Eng. 1:7