A PV/T AND HEAT PUMP BASED TRIGENERATION SYSTEM MODEL FOR RESIDENTIAL APPLICATIONS

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1. Abstract

A solar trigeneration system, based on photovoltaic-thermal (PV/T) collectors, photovoltaic (PV) modules and a heat pump unit for heating and cooling, is modelled to forecast the thermal and electric yields of the system. The aim of the trigeneration system is to provide enough electricity, domestic hot water (DHW), heating and cooling power to meet the typical demand of an urban single family dwelling with limited roof area and allow the household to achieve a positive net energy status. The PV/T collectors and PV modules provide the electricity while the former also powers the DHW component of the trigeneration system. The heating and cooling components rely on a vapour compression cycle heat pump unit powered by electricity. In Fong et al. (2010), solar-powered electric compression refrigeration was found to have the most energy saving potential in subtropical climates. Thus, a heat pump based cooling system is a cost effective solution for residential applications in Lisbon, Portugal. Thus, according to the dwelling's location, construction details and energy demand patterns, the model computes the system's net results by comparing the dwelling demand with the trigeneration system supply. The paper presents a breakdown of the proposed trigeneration system model and describes each component briefly. Preliminary results produced by the model are presented and analysed in order to identify possible ways of improving the overall system performance.

2. Introduction

A trigeneration system is capable of simultaneously generating electricity, heat and cooling power from a single power source. Such a system uses complementary processes to convert the by-products of the main energy conversion and obtain forms of energy which are in line with demand. For instance, a gas-powered turbine driving an electrical generator produces electrical energy and waste heat. The waste heat can be used to produce hot water and power an absorption chiller. The same concept can be applied in solar power plants. Solar radiation is harnessed and converted to heat used to power a turbine which then drives an electrical generator, producing electricity. Heat is an evident by-product of this conversion and can be used for the aforementioned trigeneration system. Also, solar collectors and photovoltaic modules can be used to harness solar energy and convert it to heat and electricity, respectively, which may be used to power several cooling technologies (Fong et al., 2010, Immovilli et al., 2008). The aim of this article is to demonstrate the potential of a solar trigeneration system for the residential sector by describing a model, the methodology that led to that model and analysing a set of preliminary results.

2.1 Solar Trigeneration System for the residential sector

A turbine-based solar trigeneration system is not suitable for the residential sector due to, among other concerns, scale, size, power rating, initial cost and maintenance. Instead, a solar trigeneration system developed specifically for the residential sector can be envisaged by combining photovoltaic-thermal (PV/T) technology with solar powered cooling technologies.

PV/T collectors are designed to generate electricity and heat simultaneously, thus having a higher output power density than a solar collector and a photovoltaic module with the same combined surface area. The heat generated by a PV/T collector can be used for domestic hot water (DHW) as well as heating, ventilation and air conditioning (HVAC). Absorption chiller based refrigeration powered by heat generated from PV/T collectors is possible but difficult due to high temperature requirements. Therefore, PV/T powered refrigeration can rely on conventional electric powered air-to-water vapour compression cycle heat pumps (HP). Vapour compression refrigeration is deemed the most promising solar cooling technology for the

residential market (Fong et al., 2010, Immovilli et al., 2008). Thus, a heat pump and PV/T collector based solar trigeneration system can effectively accomplish all these tasks. Local electric production can be achieved by using photovoltaic modules and photovoltaic-thermal collectors, while the latter can also be used to provide heat for DHW as well as HVAC (heating only). Solar refrigeration can be achieved by using solar powered air source vapour compression cycle heat pumps, as stated previously.

However, the proposed system fails to meet the criteria of a trigeneration system in one relevant aspect. The electricity consumed by the heat pump (while working in cooling mode) is not necessarily generated from solar power. The heat pump can only be said to be solar powered when the system is off-grid. Otherwise, the electricity is at least partially consumed from the utility grid and as a result the power source is not exclusively solar. This would mean that the energy source or "fuel" is not, at least directly, solar power. Thus, it could also be said that the grid-connected variant of this system does not necessarily represent a solar trigeneration system. Despite the ambiguity of the designation chosen, the system will nonetheless be designated as a solar trigeneration system.

2.2 System configuration

A simplified schematic of the proposed solar trigeneration system is illustrated on Figure 1. The key components of the system are PV modules, PV/T collectors, an inverter, a maximum power point tracking (MPPT) device, a battery bank, an air source heat pump and thermal storage tanks (TST) for DHW (DHW-TST) and HVAC (HVAC-TST). Several other solar trigeneration configurations are possible with these key components, though with different levels of complexity as well as parts and control requirements. This paper will focus on the simplest and most reliable configuration, i.e., the grid-connected configuration without the HVAC-TST, though the all-in-one configuration with the HVAC-TST and batteries is provided in Figure 1.
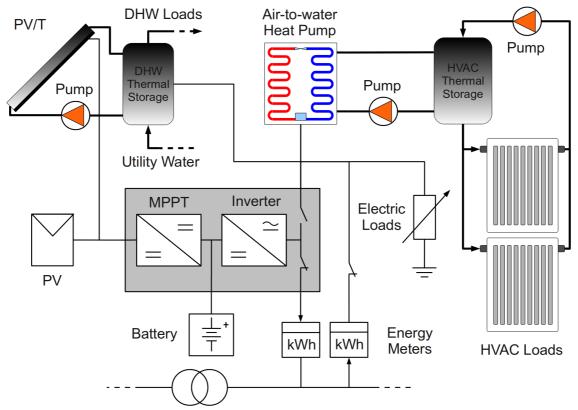

Fig. 1: All-in-one solar trigeneration system setup - relays indicate grid-connected operation

2.2.1 Electric Configuration

Electric loads, including the heat pump and the DHW backup system, can be supplied using the following electric configurations:

- Off-grid - Photovoltaic production can be used to supply the electric loads when solar power is available and charge the batteries when production exceeds demand. If charged, the batteries can be used to supply power when there is no solar power available and when demand exceeds production.

- Grid-connected - Electric loads are supplied exclusively by the utility grid while local photovoltaic production is entirely delivered to the electric grid using a separate connection and energy meter.

- Backup - In this configuration, the system is grid-connected but also incorporates local electric storage. This can be useful to operate the system as an uninterruptible power source (UPS) should the utility grid fail to supply the household with electricity or, possibly delay the delivery of electric power to the utility grid, which may be beneficial for a wide variety of reasons. An adequate inverter must be used in this situation, usually known as a backup (system) inverter.

The all-in-one schematic proposed in Figure 1 is effectively capable of operating under every configuration. However, depending on the configuration, the actual setup should be a simplified version of the original since some components are not necessary.

2.2.2 Thermal Configuration

The thermal configuration concerns the ways in which the thermal loads can be supplied. Thermal loads are divided into DHW loads (showers, dish-washing, etc) and HVAC loads (heating and cooling). The HVAC demand loop may include radiators and/or fan-coils while the DHW demand loop can include taps, diffusers, etc. Thus, the proposed system operates under the following set of rules:

- DHW loads are supplied exclusively through the DHW-TST while HVAC loads may or may not be supplied exclusively through a HVAC-TST;

- The HP is used to heat up or cool down an optional HVAC-TST or HVAC thermal loads directly;

- The PV/T collectors are used to supply heat to the DHW-TST;

- Backup power can be provided to the DHW-TST via an immersible electric heating element which can effectively heat up the DHW-TST when solar power is insufficient or simply not available.

The simplicity of the operating mode allows for increased reliability and lower installation and maintenance costs. The presence of a HVAC-TST is optional and will increase initial costs, maintenance and installation space but it allows for increased flexibility, which may prove important to optimize system performance.

2.2.3 Market Potential

PV/T collectors are better suited for urban settings than conventional solar collectors and photovoltaic modules. According to a study by Silva and Fernandes (2010), to match the performance of their sheet and tube PV/T setup with PV modules and solar collectors would require an additional 60% of installation area. Hence, PV/T collectors are well suited for densely populated urban areas where roof space is scarce.

Also, electric driven vapour compression refrigeration is believed to be the most cost effective cooling solution for the residential sector mainly due to efficiency, simplicity, reliability and a consolidated market (Immovilli et al., 2008). Thus, a solar trigeneration system based on a PV/T solar DHW system and electric driven vapour compression cooling is a feasible and competitive solution for the residential sector.

Regarding the electric configuration, the grid-connected system configuration without batteries is by far the most appealing, marketwise. Legislation on distributed energy resource systems differ from country to country and not all grid-connection schemes are allowed but most allow the standard grid-connection scheme. Also, grid-connected inverters are also more attractive when levelled against off-grid and backup inverters, particularly because of price, warranty, simplicity, maintenance and overall robustness. Off-grid and backup systems also need batteries and may require separate MPPT devices. Nevertheless, off-grid systems are a matter of necessity, urgency or cost-effectiveness for those in need of energy supply, particularly in areas poorly or simply not reached by the distribution grid.

3. Trigeneration System Model

3.1 Objectives

The system model is a tool for understanding and predicting the performance of a trigeneration system as well as sizing it. A definitive model is one that not only covers the most distinctive phenomena associated with a process, but also those believed to be secondary in nature. However, certain aspects of the system

performance, which are deemed to be of secondary nature, can be overlooked if properly justified according to the specified objectives. For instance, the detailed transient behaviour of an inverter or charger does not contribute to an increased understanding of the fundamental aspects of the trigeneration system performance and as such, can be neglected and a power-based steady state model used instead. Also, it goes without saying that including detailed power electronics models would make simulations much slower and require additional modelling efforts. On the other hand, detailed collector and storage tank models are important to understand the dynamics of the system and must be included.

3.2 Methodology

A typical modelling methodology consists of separating the system model into smaller, less complex models which can be validated independently of each other, and once every independent model has been validated, proceed to a higher level of validation, integrating two or more components and validating their combined behaviour. Such a modular approach can be particularly helpful in identifying inaccurate or incomplete models as well as fine-tuning application specific controllers or models.

The system can be conceived as three separate entities - climate, building and trigeneration system - with multiple interactions between them. Thus, we can divide the system model into the following submodels:

- Climate model - The climate model mimics the variations of relevant climate variables over a designated time period;

- Trigeneration model – The trigeneration model reproduces the behaviour of the trigeneration system components, namely photovoltaic-thermal conversion, HVAC system and thermal and electric storage, with regard to local climate data as well as load profiles;

- Building model - The building model accurately portrays the requirements for thermal comfort inside a building or household according to local climate variations and also reproduces electric load profiles and typical domestic hot water consumption.

In a practical sense, these models represent highly dynamic systems which are not altogether independent and whose interactions must be taken into account. Yet, for the sake of simplicity and feasibility, some components are considered static. For instance, the climate model is known to have a decisive influence on all other models but can also be said to be influenced by the remaining models. However, it is assumed that the climate model is not influenced by the dynamics of other models, which can be aptly translated as considering the surroundings as being effectively a large thermodynamic reservoir - a reasonable assumption on most accounts. Another simplification relates to the cumbersome if feasible task of modelling a household's dynamic behaviour, which was avoided by assuming the building's behaviour to be independent of whether or not local demand is met. This assumption is valid if power is continuously supplied to the household, so it can be used for HVAC, meaning it must be either a grid-connected system with no power outages or an off-grid system with little or no loss of load occurrence. For example, if for some reason, the HVAC thermal demand is not met, afterwards, the thermal energy required to achieve comfort levels would be much higher than it would be if HVAC thermal demand had been met previously. However, the building model has no way to account for this deviation, due to its static behaviour regarding HVAC supply, meaning that the HVAC thermal demand is exactly the same whether or not it has been met in the past.

The aforementioned assumptions result in a system model, displayed in Figure 2, with minor deviations regarding what had been previously conceived as the definite system model.
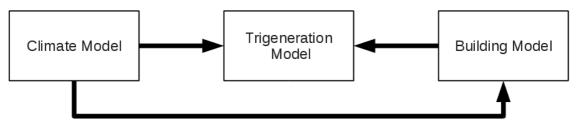

Fig. 2: Trigeneration system model methodology

3.3 Simulation Tools

Several simulation environments exist to facilitate these modelling efforts, namely *TRNSYS* (Kalogirou, 2001; Kalogirou and Tripanagnostopoulos, 2006; Zondag et al., 2003), *MATLAB/SIMULINK* (Silva and Fernandes, 2010), *EES* (Charalambous et al., 2011) and *ESP-r* (Cartmell et al., 2004). Among these, we have identified *MATLAB/SIMULINK* as incorporating the necessary features for the implementation of the proposed trigeneration system model. The *MATLAB/SIMULINK* features our team has deemed the most valuable are, among others, a user-friendly interface, flexibility, cross-platform capabilities, comprehensive libraries of building blocks and more importantly, the ability to create custom blocks easily while providing adequate debug features. Past experience with the simulation software also played a key role in the decision making process. Due to the high number of models developed for this project and the prospect of improvements to some models, a custom *MATLAB/SIMULINK* library was developed to accommodate them.

The trigeneration and climate models were mostly developed using *MATLAB/SIMULINK* whereas the building model was mostly conceived using *DesignBuilder*, a building performance analysis software. According to the current Portuguese legislation on Building Energy Performance (Decreto-Lei nº 79/2006), building thermal analysis on Portuguese buildings must be conducted using a software program which follows the ASHRAE 140-2004 standard (ASHRAE, 2004), *DesignBuilder* being one of those software programs. *DesignBuilder* is in fact closer to a building editor since it uses *EnergyPlus*, a simulation engine developed by the United States Department of Energy, to handle simulations.

3.4 System Model

The system model follows the approach suggested by Figure 2. Thus, climate data is provided in advance by the climate model, which is used for the building and trigeneration models. The building model determines the electric and thermal loads according to climate data and building parameters, and provides this information to the trigeneration model. The trigeneration model acts as an energy conversion and storage model, handling local production (PV, PV/T and HP), storage dynamics (battery and TSTs) and local demand (electric, HVAC and DHW loads). The trigeneration model was conceived according to the power flow diagram provided in Figure 3. As made evident by the figure, the trigeneration model includes several submodels namely a PV array model, a PV/T collector array model, a TST model, a HP model, an electric battery model, various tunable controllers, a simplified steady state inverter model, a cable losses estimation model, among others. Brief descriptions of the key component models will be provided.
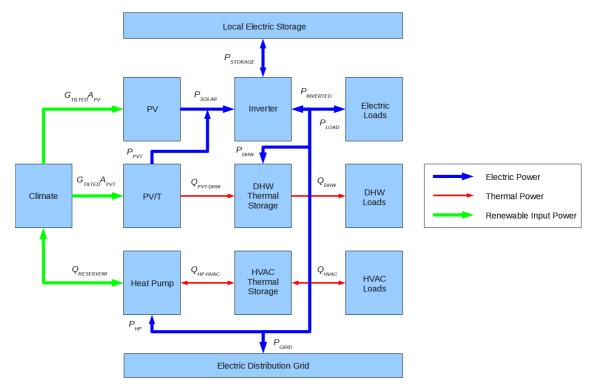

Fig. 3: Solar trigeneration system model power flow diagram

3.4.1 Climate Model

Reference climate data for a Lisbon located dwelling was supplied by the LNEG-developed *SOLTERM* software program. The climate variables used by the model are ambient temperature, beam irradiance on a horizontal plane and diffuse irradiance on a horizontal plane. Data regarding wind speed and tap water temperature, which are required by some models, were not available and were assumed constant and estimated, respectively. In any event, a formatted file containing these variables is easily uploaded to the *MATLAB/SIMULINK* environment, where they can be used.

Regarding the variables which were available, the ambient temperature is relevant for a wide variety of reasons, namely to determine the PV modules' temperature and output power, the PV/T collector thermal and electric output power and the heat pump efficiency. The irradiance components are used to compute the tilted plane irradiance using an isotropic tilted plane irradiance model as described in Duffie et al. (2006). Anisotropic tilted plane irradiance models were also tested but the isotropic model proved to be the most conservative and as such, was selected. The sun's position – a requirement for tilted plane irradiance models - was estimated on an hourly basis using the horizontal coordinate system.

3.4.2 Building Model

The building was mostly modelled using *DesignBuilder* which computes the annual demand for thermal comfort inside a building in one hour steps. Additionally, tools are provided to shape the occupancy schedules and daily electric load profiles (lighting and appliances). *DesignBuilder* can export the data so that it can be accessed by other software programs. The DHW load profile was developed separately in *MATLAB/SIMULINK* by writing a pulse generator routine that repeats a pattern over a designated time period. This allows users to define separate DHW patterns and combine them into one with a sum block.

3.4.3 PV Module Model

The behaviour of PV modules was modelled using a linear steady state model based on the maximum power point. This is a valid approach if the PV array is connected to a MPPT device. Also, since the inverter model is reduced to its steady state version and climate data is only available on an hourly basis, there is little justification to use the single or twin diode equivalent circuit model.

3.4.4 PV/T Collector Model

A PV/T collector based on the sheet and tube design was modelled as a set of one-dimensional energy balance equations - an adequate approach for determining the transient response of PV/T collectors (Zondag et al., 2002). The model itself is similar to the one proposed by Silva and Fernandes (2010) though adjusted to reduce computational requirements and therefore facilitate its integration into the system model.

3.4.5 Heat Pump Model

The HP is modelled as an electric load using manufacturer supplied efficiency tables. Hence, if a thermal power reference - the building thermal power demand - is provided, the electric power required to operate the HP can be computed. A downside of this model is that it does not account for the HP internal protection mechanisms, namely control and timer-based restart prevention, instead focusing on a steady state approach.

3.4.6 Thermal Storage Tank Model

Thermal stratification is an effect that decisively influences the performance of solar collectors (Duffie et al. , 2006; Santbergen et al., 2010). Thus, a TST model capable of mimicking stratification is required to properly evaluate the performance of solar collectors. A TST was modelled according to the multi-node energy balance model proposed by Nelson et al. (1999), which considers heat transfer to the surroundings, conduction from warm layers to cold layers, conduction through thermocline and thermal mixing.

4. Simulation

Accurate appraisal of the proposed trigeneration system requires extensive simulations which must rely on trustworthy models and component parameters consistent with existing climate and materials. The grid-connected system variant without the HVAC-TST was simulated even though the model is capable of simulating the remaining configurations. The next subsections detail the parameters used in the simulations.

Building Model Parameters

Simulations were conducted on a dwelling modelled with *DesignBuilder* and using Lisbon weather data. The building is a single family dwelling for four occupants with 2 floors, an attic and a total area of 225 m².

The building's construction elements are in accordance with Portuguese building codes (Decreto-Lei nº 80/2006). Among them, the thermal transmission coefficient (U) of the windows is 4.3 W/m²K and the solar transmission factor (SHGC) is 0.45. The lighting density is 5 W/m² and the equipment density is 14 W/m². The occupancy schedules and the electric load profiles were specified according to a typical week with five working days. The electric load profiles were shaped so that annual consumption would resemble the 2009 Portuguese average annual domestic electric consumption for a dwelling with four occupants: 5337.6 kWh or 1334.4 kWh per occupant (Instituto Nacional de Estatística, 2011). The household does not have mechanical ventilation but as a result of Lisbon's location, wind exposition, windows' airtightness and façade height, the building has 0.9 air changes per hour. The HVAC units selected for the simulation were fan-coils. The space setpoint temperatures were defined as 20ºC during Winter time and 25ºC throughout the Summer.

Showers take place during the morning as part of the worst case scenario approach to system sizing. DHW consumption was estimated by Zondag et al. (2001) according to typical standards and amounts to about 175 litres at temperatures between 45ºC and 55ºC. However, due to thermal losses the actual consumption of water at 60ºC was found to be 139 litres per day (Zondag et al., 2001). This is roughly equivalent to an annual thermal demand of 2811 kWh, according to the estimated local tap water temperatures. Also, the DHW-TST is kept at a minimum of 60ºC, via backup system, to prevent growth of the *Legionella* bacteria.

Climate Model Parameters

Lisbon is located at 38º42'N and 9º8'W. The climate is considered to be Subtropical-Mediterranean. Reference outdoor temperatures are displayed in Figure 4, with monthly averages ranging from about 10ºC in the Winter months (December, January and February) to about 25ºC during the Summer months (June, July and August). The tap water temperature is assumed to be 10ºC during the Fall and Winter months and 15ºC during the Spring and Summer months. Also, according to the irradiance model used (ground diffuse reflectance at 10%), maximum annual irradiation occurs at a south facing 30º slope with the horizontal plane.
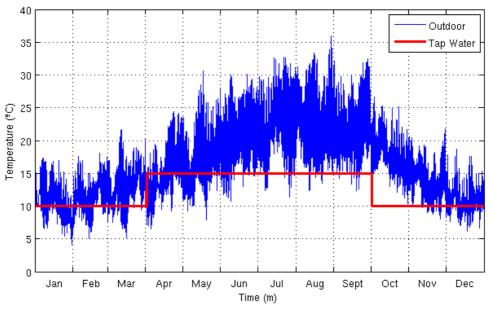

Fig. 4: Reference outdoor temperatures for the Lisbon municipality and assumed tap water temperatures

Trigeneration Model Parameters

Simulations were conducted with 23.38 m² of PV module area and 6.68 m² of PV/T collector area, which amounts to a total combined area of about 30 m². The relevant electric properties of the PV modules are displayed in Table 1, whereas the PV/T collectors' thermal and electric efficiencies are show in Figure 5. The PV/T collectors exhibit maximum thermal and electric efficiencies of about 59% and 14%, respectively. Both PV modules and PV/T collectors were simulated facing south at a 30º slope with the horizontal plane.

Tab. 1: Parameters of the PV modules under STC conditions

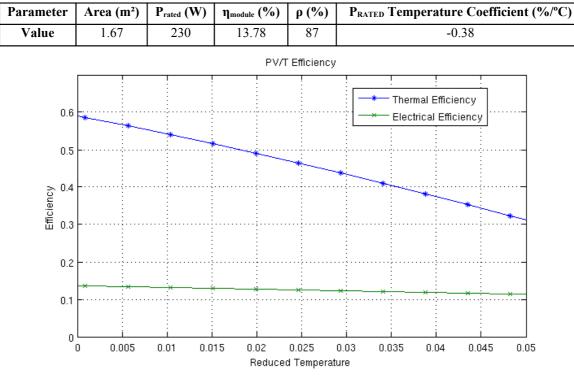| Parameter	Area (m²)	P_{rated} (W)	η_{module} (%)	ρ (%)	P_{RATED} Temperature Coefficient (%/ºC)
Value	1.67	230	13.78	87	-0.38

Fig. 5: Thermal and electric efficiencies of the single cover *sheet and tube* PV/T collector

The PV modules' and PV/T collectors slope angle was chosen to match the angle at which the solar irradiation is maximum in order to maximize electric production, since the simulated setup is grid-connected. The solar DHW component was simulated with a differential temperature controller with 10ºC and 2ºC thresholds for on and off modes, respectively, a specific flow rate of 10 Kg/m²h and a TST model with three vertical nodes - the TST parameters are specified in Table 2. A commercial air-to-water heat pump unit with adequate power rating was selected and modelled due to its overall high operating efficiencies – see Table 3.

Tab. 2: Domestic Hot Water Thermal Storage Tank (DHW-TST) Parameters

Parameter	Volume (m³)	Inner Surface Area (m²)	U_{ext} (W/m²K)
Value	0.2	2	1

Tab. 3: Efficiency table of the selected air-to-water HP

Heating Mode								Cooling Mode								
T_{air} (ºC)	T_{water} (ºC)							T_{air} (ºC)	T_{water} (ºC)							
	25	30	35	40	45	50	55		5	6	7	8	12	16	18	20
-15	2.67	2.35	2.05	1.72	-	-	-	28	3.27	3.39	3.5	3.53	3.91	4.21	4.41	4.56
-10	3.03	2.62	2.21	2.02	1.76	-	-	32	3.11	3.15	3.23	3.34	3.63	3.92	4.1	4.33
-5	3.52	3.08	2.56	2.33	2.06	1.76	-	36	2.72	2.82	2.86	2.92	3.21	3.47	3.64	3.84
0	4.09	3.57	3.12	2.78	2.5	2.15	1.83	40	2.39	2.46	2.51	2.58	2.84	3.08	3.23	3.36
5	5.34	4.51	3.95	3.51	3.15	2.57	2.09	45	1.96	2.07	2.12	2.2	2.38	-	-	-
10	6.06	5.28	4.54	4.05	3.66	2.96	2.42	-	-	-	-	-	-	-	-	-
15	6.81	5.92	5.07	4.52	4.13	3.33	2.9	-	-	-	-	-	-	-	-	-
20	7.56	6.58	5.63	5.02	4.57	3.8	3.3	-	-	-	-	-	-	-	-	-

The HP model controller was set to produce cold water at 7ºC and hot water at 35ºC. Then, according to the reference outdoor temperatures seen in Figure 4 – from 4ºC up to 36ºC, the HP unit should operate at efficiency values ranging from 3.12 up to 5.63 in heating mode and from 2.86 up to 3.5 in cooling mode.

5. Simulation Results and Analysis

Building Simulation Results

The building was simulated and produced the annual thermal demand for heating and cooling in one hour steps as displayed in Figure 6. The annual thermal energy demand to reach predetermined comfort levels amounts to 4842 kWh of energy that must be provided to the household (displayed in red) and 1552 kWh of energy that must be extracted from the household (displayed in blue). The plot displays thermal energy in one hour steps, meaning that the HP can either operate at constant power during one hour or at variable power, as long as the same energy is transferred after one hour. The former method is used by the HP model.
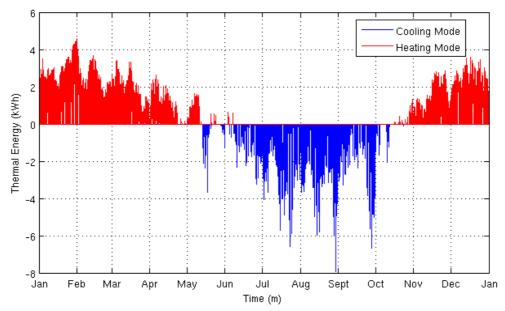

Fig. 6: Thermal energy that must be provided to (red) or extracted from (blue) the household to meet comfort levels

If thermal energy was exclusively provided by typical electric heaters – a common scenario in Portugal, the annual electric energy required to power the electric heaters for heating alone (about 4600 kWh, assuming 95% conversion efficiency) would reach about 86% of the 2009 average annual domestic electric consumption in Portuguese households with four occupants (Instituto Nacional de Estatística, 2011). However, if the same energy is provided by the heat pump, the annual electric energy consumption for heating alone is expected to be between 860 kWh (at an efficiency of 5.63) and 1551 kWh (at an efficiency of 3.12) or between 16% and 29% of the 2009 Portuguese average annual electric consumption, respectively.

System Model Results

The model was run and produced the results found in Table 4. The annual electric demand adds up to 6188 kWh which exceeds the Portuguese average electric energy consumption by 850 kWh or by about 16%. This is mostly due to the DHW backup system since it requires considerable electric power to operate and operates all year. Also, DHW in Portuguese households is usually provided by gas-powered heaters which can adequately justify the disparity between the actual electric demand and the national average electric consumption mentioned earlier. Nonetheless, an annual thermal solar fraction of 64% was achieved. The annual electric solar fraction (i.e., the ratio between local photovoltaic production and total electric demand) was found to be 103% which is a testament to the system's positive net energy balance – the net total amounts to 209 kWh, as seen in Table 4. The monthly progressions of both solar fractions can be observed in Figure 7. As displayed in the figure, system performance is aggravated by electric demand during the Winter, mostly due to HP and DHW backup system operation, and gradually improves as the Summer gets closer, mainly because of peak production levels - PV modules and PV/T collectors were simulated at the slope angle which provides the maximum annual irradiation (1596 kWh/m² at a 30º south facing slope).

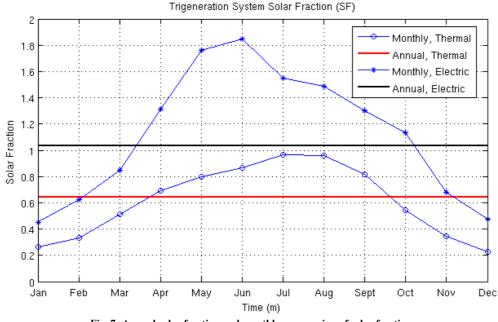| Electric	Annual Production (kWh)		Annual Demand (kWh)					Net Total (kWh)
	PV/T	PV	Building (HP)		DHW	Miscellaneous		
			Heating	Cooling		Lighting	Appliances	
Individual	1302	5493	1152	443	1251	1102	2240	-
Total	1302 + 5493 = 6795		1152 + 443 + 1251 + 1102 + 2240 = 6188					607
Inverted	6397		6188					209

Fig. 7: Annual solar fraction and monthly progression of solar fraction

The slope angle was selected because the system is grid-connected and as such, it makes no difference to the consumer if the electric energy is delivered evenly throughout the year or mostly during the Summer. However, the same is not true from the point of view of (PV/T) thermal performance. Thermal performance is bound by storage and constant demand dynamics and therefore requires a steadier supply of solar power throughout the year, namely during the winter. This can be done – up to a point - by increasing the slope angle on the PV/T collectors which increases irradiation when the sun is in low solar altitude positions (Winter) and decreases irradiation when the sun is in high solar altitude positions (Summer). At the same time, electric demand could fall during the Winter due to less frequent use of the DHW backup system. On other hand, PV/T collectors also provide electric power which may prove more important for a variety of reasons, namely due to a competitive feed-in tariff. Hence, this is effectively a multi-objective optimization problem and while not the focus of the present work, is a relevant subject and deserves careful examination.

The PV modules and PV/T collectors generated 5493 kWh and 1302 kWh of electric energy at average efficiencies of 14.7% and 12.2%, respectively. These results can be explained by the relative low temperatures of the PV modules – averaging 30.7ºC during operation – and by the reduced optical efficiency and higher cell temperatures of the PV/T collector – averaging 46.6ºC when operating. The annual variation of cell temperatures, for both PV modules and PV/T collectors, is displayed in Figure 8. The electric system efficiency (inverter and cables) was found to be 94% which resulted in an annual output of 6397 kWh.

The PV/T collectors also delivered 1618 kWh of thermal energy to the DHW-TST, operating at an average efficiency of 15%, a small figure compared to results presented by Santbergen et al. (2010) which operated at 24.3%. DHW loads amounted to 2523 kWh, which differs from the optimal value predicted earlier – 2811 kWh - because of high frequency demand during the mornings which degrades the temperature profile in

stratified TSTs. This effect can be measured by a quality of service indicator which relates the actual DHW energy supply with the optimal DHW energy supply. According to the simulation results, the quality of service would be close to 90%. The difference between the heat delivered by the PV/T collector and the heat extracted from the DHW-TST, either for consumption or due to thermal losses, is provided by the backup system which consumed 1251 kWh of electricity. Overall, the solar DHW system performed well, with average solar fraction values similar to those found in Santbergen et al. (2010) and Silva and Fernandes (2010). However, low insolation forces the system to use backup power, which reduces the solar fraction considerably since the backup system uses a simple submersible electric heating element. However, this task would be handled far better by running the heat pump to preheat the DHW-TST up to a temperature of 55ºC operating at efficiencies between 1.83 and 3.3. This would increase the initial cost, complexity of the system and controls but would also increase the solar fraction (by reducing electric demand) which would compensate its shortcomings in the long run. Another possibility is to use a "tankless" heater which would heat up the water leaving the DHW-TST up to 60ºC, if necessary, and not the DHW-TST itself. This would prevent the DHW backup system from tampering with the thermal efficiency of the PV/T collectors by increasing the temperature of the water stored in the DHW-TST. This seems to be the strategy used in Santbergen et al. (2010) which provided increased thermal efficiency. It should be mentioned that human health is paramount and as such, a solar DHW system must include a backup system, operating to meet local thermal demand, if necessary, as well as to prevent the growth of the *Legionella* bacteria.
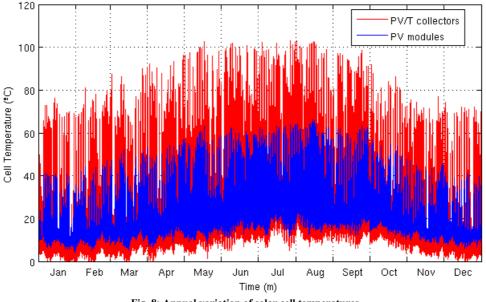

Fig. 8: Annual variation of solar cell temperatures

The selected HP performs well and reaches annual average efficiency figures of 4.25 (heating) and 3.5 (cooling). The HP consumed 1595 kWh of electric energy, 1152 kWh in heating mode and 443 kWh in cooling mode, as seen in Table 4, which amounts to 26% of total annual electric demand. However, the HVAC performance could be substantially improved by operating the heat pump when the weather is favourable to high efficiency operation and then storing cold or hot water in a HVAC-TST for later use. This type of strategy could improve the overall system performance but must be further studied to account for tank thermal gains or losses, predictive errors regarding thermal demand and operation scheduling.

6. Conclusions

The methodology used to produce this model proved adequate. The model is effectively capable of reproducing some - though not all - phenomena associated with photovoltaic systems, solar DHW systems and HVAC systems. The simulation results were used to demonstrate this point as well as to provide the background against which potential improvements could be evaluated or compared – a basic configuration. The proposed solar trigeneration system model was simulated and showed good results under Lisbon climate but still requires fine-tuning. Nonetheless, the trigeneration system is a feasible and competitive solution for the residential market namely as a bundle of a photovoltaic system, solar DHW system and HVAC system.

The authors have identified several ways to improve system performance, namely by using the HP unit to preheat the DHW-TST instead of using an electric heating element. On the other hand, system performance is intrinsically related to supply, demand and storage dynamics. Thus, all three aspects have to be considered if system performance is to be optimized. Future work will focus on improving existing models, namely the HP model and the HVAC loop in particular. Efforts will also focus on studying different system configurations, optimal sizing as well as economic considerations regarding sub-optimal sizing.

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