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Trigeneration for domestic purposes in isolated areas based on hybrid RES

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Abstract. The design of a system providing electricity by coupling photovoltaic/thermal (PVT) collectors and a wind turbine (WT), sanitary hot water (SHW) coming from the PVT and evacuated tube collectors (ETC) and fresh water (FW) produced in two seawater desalting facilities (membrane distillation, MD, and reverse osmosis, RO), has been carefully analyzed by means of a dynamic model developed in TRNSYS. This analysis was the base for the lab-scale pilot plant that has been recently installed in Zaragoza, Spain.

Coverage of SHW, water (including RO and MD) and power is respectively 99.3%, 100% and 70% in the model. Later tests should validate this very promising results obtained in the simulation at affordable costs in the case of isolated areas.

Key words
Dynamic simulations; photovoltaic/thermal; wind turbine; membrane distillation; reverse osmosis; hybrid systems; energy in isolated areas.

1. Introduction

Apart from producing energy and water with hybrid techniques and renewable energy sources (RES) in cogeneration schemes, there are very few examples of the analysis of tri-generation or poly-generation schemes involving seawater desalination and RES. In [1-2], a poly-generation system based on PVTs, a LiBr-H2O chiller, and a MED distiller, with a back-up biomass heater was simulated and optimized in TRNSYS® with weather data from Naples, Italy. A similar scheme could be optimized by GAMS in its design and operation if conventional energy sources are neglected in the superstructure presented for a polygeneration applied to tourist sector [3].

From the previous analysis, it can be observed that the combination of hybrid techniques for both RES and desalination, which also includes SHW, has not been studied in detail yet. Thus, this paper presents the design analysis of a double hybrid scheme (wind/solar+MD/RO) which allows providing power, SHW and fresh water at a much reduced demand scale in isolated areas. This hybridization is a technically possible solution and its profitability will depend on alternative costs to provide water and energy by a network or even local transport.

Taking into account the variability of the renewable energy sources, a dynamic simulation is required in order to model and then to assess the performance of the transient processes occurring in that scheme. Dynamic simulation of this trigeneration system was performed in TRNSYS software (v16). Its modular design easily permits to analyze the main design parameters of each component but also the overall performance of the scheme proposed, according to scheduled energy and water demands.

This work presents the base design of a small hybrid-trigeneration pilot plant, which has been erected at the University of Zaragoza. The initial prerformed simulation of the configuration was the background of the real pilot plant. Specifically, the diversion of the hot water flow leaving the water tank to feed the MD or to cover the SHW demand is being carefully analyzed in the field tests, according to important variations found in the simulations performed regarding the FW produced by the MD.

2. Plant layout

Main subsystems included in the hybrid trigeneration scheme are shown in Figure 1.

The whole system has been divided in five subsystems. 1) The solar loop, where solar energy is collected and transformed into thermal energy and electricity. 2) SHW, where thermal energy is delivered to the tap water to increase its temperature. 3) Membrane distillation. 4) Reverse Osmosis and 5) Power loop. Table I shows these five subsystems and the main units for the proposed design (base case).

Table I. – Subsystems in the pilot unit.

SUBSYSTEM	UNITS, SIZE
Solar Loop	Four PVT collectors, 1.63 m^2 at 40º
	One ETC, 1.4 m2
	One AC pump, 5 W
SHW	One tank with heat exchanger, 325 L
	One diverter valve
	One T valve (V-SHW)
	One AC pump, 5 W
	One tempering valve
MD	Spiral wound distillation module (Permeate Gap Membrane Distillation type, PGMD), maximum distillate 20 L/h
	One AC pump (heat exchanger), 5 W
	One DC pump (MD system), 10 W
	One counter-flow heat exchanger
RO	Reverse Osmosis unit, 110 W, permeate 35 L/h
Power loop	Four PVT collectors, 240 Wp
	One wind turbine, 400 Wp
	Two batteries, 250 Ah and 24 V

Power generated in the PVT subsystem (4 x 240 W_p) is driven to a regulator which protects the battery against overcharge or deep discharge. Wind turbine was simulated in TRNSYS through a numerical model that adjusts the power-velocity curve of a commercial model (400 W_p). This unit is also connected to the regulator. A set of two batteries (250 Ah and 12 V) connected in series accumulates that power for further needs. Electric demand consists in the power required by 3 AC pumps of 5 W (pump 1 in solar loop, pump 2 for hot water to MD heat exchanger, and pump 3 for SHW), one DC pump of 10 W used by the MD loop, and finally the power consumed by the RO (110 W, DC). Remaining power could be used to partially cover the domestic power demand or stored in the batteries.

A. Demands

Electric and water demands considered in this investigation were based on a single family home in Spain. The electric demand from this kind of home is about 2422.2 kWh per year [4]. The system is connected to the grid to partially supply demand when the batteries power is not enough. Additionally, the total fresh water demand is estimated in 106.4 cubic meters per year, and SHW demand in 37.2 m^3/y [5]. Water demands are firstly covered through the storage tanks (hot water and fresh water); anyway tap water and an electrical storage water heater could supply the remaining demands. Table II shows daily water demands (cold and hot) for a single family home as well as the average electricity consumption per day.

Table II. – Water and energy demands (day^{-1}).

MONTH	FW (L)	SHW (L)	POWER (Wh)
January	300.4	105.1	6626.8
February	302.7	105.9	6657.4
March	302.8	105.9	6678.1
April	300.9	105.3	6646.7
May	281.7	98.6	6646.3
Jun	281.8	98.6	6673.6
July	280.3	98.1	6652.1
August	281.7	98.6	6646.3
September	281.8	98.6	6673.6
October	280.4	98.1	6652.1
November	302.2	105.7	6644.4
December	299.2	102.4	6658.3

B. RES sources

In order to assess the available renewable resources, meteorological data from the place where the trigeneration system was established were taken. In this case, Zaragoza city, located in the northeast of Spain, was the chosen one. As previously mentioned, data were obtained from Meteonorm data base and were introduced in TRNSYS® as a file-input. Figure 2 shows the behaviour of solar radiation (40º tilt), wind velocity at wind turbine height (13 m) and ambient temperature along the year at Zaragoza, Spain.

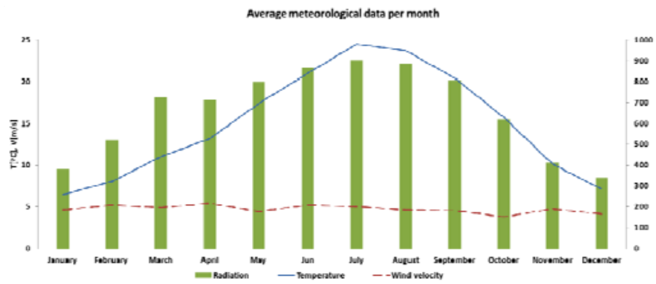

Fig. 2. Zaragoza meteorological data

C. Simulation

Standard TRNSYS types were used for the majority of devices included in the hybrid scheme. Nevertheless, a new type was specifically defined to simulate and validate the MD unit which produces desalted seawater, whereas RO unit was modelled as an electric load coupled to the battery.

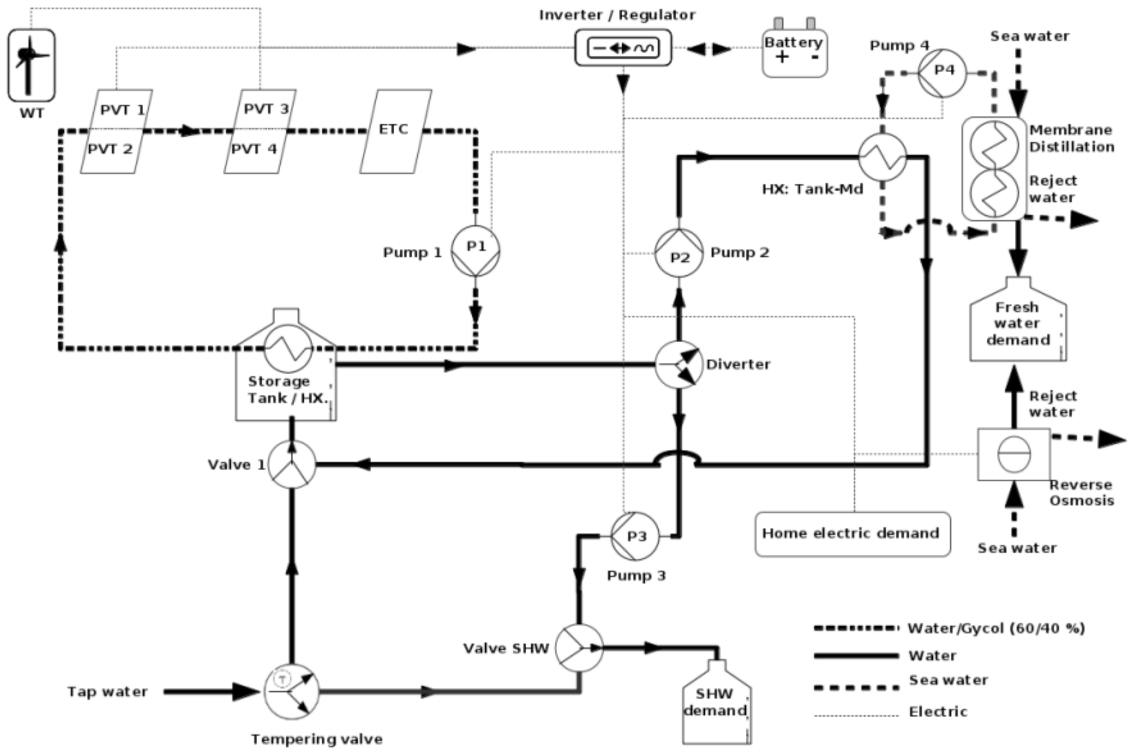

Fig. 1. General description of the hybrid trigeneration system for domestic purposes.

3. Simulation results

A. Base case

Table III shows the annual production of SHW, FW and electricity for the base case of this preliminary design, according to main data included in table I.

Table III. – Production and coverage in the base case.

	PRODUCTION	DEMAND	COVERAGE
SHW	36,990 L	37,000 L	99.3 %
FW (MD + RO)	15,311 + 306,607 L	106,421 L	302%
Power	1,890 kWh	2,711 kWh	70 %

It is interesting to note that in the case of the SHW, it is not possible to fulfil the demands imposed to the dwelling in winter days, since the SHW service temperature is not reached in this period, mainly due to the use of that SHW for activating the MD unit (70°C).

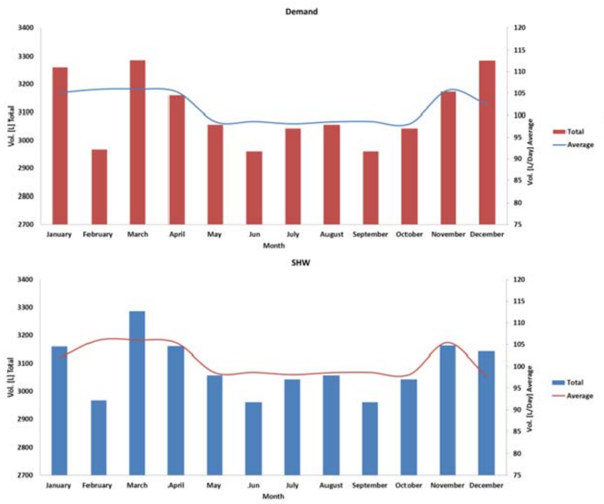

Fig. 3. SHW demand (red) and production (blue) along the year (base case).

B. Optimized design

In order to improve the first design, production of SHW, FW (mainly the produced by the MD unit) and electricity is expected to rise up as much as possible. Six free-design variables of the first scheme were independently varied in the model: collector scope, ETC area, storage capacity, MD flow rates, % of use to SHW and battery capacity. Best option corresponds to 40º, 2 m^2, 325 L, 500 L/h, 100% and 250 Ah respectively. Table IV shows the production, demand and coverage in the optimum case.

Table IV. – Production and coverage in the optimum case.

	PRODUCTION	DEMAND	COVERAGE

SHW	37,100 L	37,000 L	100.3 %
FW (MD + RO)	20,745 + 306,607 L	106,421 L	304%
Power	1,997 kWh	2,711 kWh	75 %

C. Comparative analysis

First, and within the SHW production, in general not major differences between the base case and the optimum case were found. The same happens with the electricity production (see Fig. 4). However, great differences are found in the FW production: contrary to the SHW and electricity productions, MD distillate is not continuously produced along the year. As it was restricted by the storage tank temperature (70°C), in winter season thermal energy collected by the PVT and ETC is not usually enough to produce distillate. Fig. 5 shows those differences, which also could be measured in terms of number of days per month in which the MD module was not activated in a typical year.

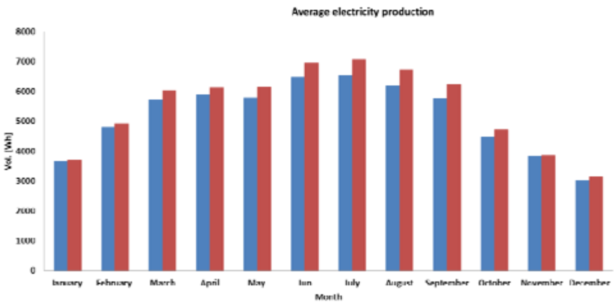

Fig. 4. Power generated in the base (red) and optimized case along the year.

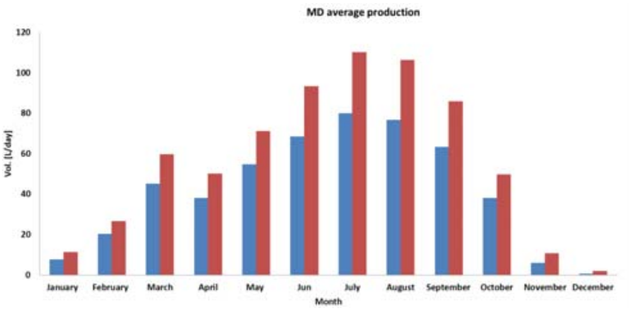

Fig. 5. Distillate produced by the MD unit along the year.

4. Economic analysis

A simple economic feasibility study of the hybrid plant is presented in this section. To assess the costs of desalted water, SHW and power, the investment costs of the devices associated to the generation of each product were taken into account. In the analysis, investment costs of the MD and RO units were taken into consideration to estimate water costs. Regarding SHW, a portion of PVT, the ETC, water tank, pumps and regulation valves were considered. Finally, to account for the power costs, the remaining investment required in PVT, wind turbine, batteries and regulator-inverter was introduced. The life cycle assumed for all devices was 20 years. Table V shows those costs.

Table V. – Production and coverage in the optimum case.

	FW (€/m^3)	SHW (€/m^3)	POWER (€/kWh)
Base	3,20	3,78	0,106
Optimum	3,15	3,84	0,100

5. Plant layout

Main figures of that simulation were used to build up a small hybrid-trigeneration pilot plant, which has been erected at the facilities of the University of Zaragoza. Specifically, a control valve that splits the use of hot water to feed the MD or to cover the SHW demand was inserted in the layout, according to important variations found in the simulations performed. The plant is now being characterized specifically for every device of the pilot unit, and the control system has been monitored in order to gather the main important variables of the pilot unit. Some pictures are included in the paper in order to see the overall view of the scheme.


Fig. 6. External set of RES devices: PVT, ETC, microwind turbine.


Fig. 7. Detailed picture of the MD unit.

Fig. 8. Permeate produced by the RO unit.

Fig. 9. Control system of the pilot unit.

6. Conclusion

A small pilot plant consisting of two renewable energy devices (PVT and WT) providing power and SHW, as well as two fresh water desalting technologies (MD and RO), has been carefully modelled here. Only commercial devices were used in the design analysis, although the regulation and control was specifically designed. The case study was located in Zaragoza city, Spain. Transient simulation software TRNSYS version 16 was used for this purpose. This software has been proved as a powerful tool to simulate the trigeneration installation during the design stage, since it allows assessing the overall performance of the system along a complete year.

Design optimization was concentrated in the maximization of the MD distiller. This was found by varying the tank temperature or the flow rate operating in the MD. Thus, SHW is the same in base case and optimum case. However, a 7% power production increment was found in optimum case with respect the base case, and it was increased a lot the MD production (35%). Only the internal power demands are not totally fulfilled by the hybrid plant (around the 70%); nevertheless FW produced by the RO should be reduced (it cover the 300% of FW demand) and could improve that power coverage.

Water, SHW and power costs found in the optimum case are around 3.15 €/m^3, 3.84 €/m^3 and 0.10 €/kWh respectively, being this scheme one feasible alternative for small isolated family homes. Nevertheless, water produced by MD is by far the highest one, and those costs are not competitive in grid-connected systems, especially for the water network.

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