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TESI

DYNAMIC MODELING AND EXPERIMENTAL ANALYSIS OF A TRI-GENERATION PLANT FOR THE PRODUCTION OF ELECTRIC, THERMAL ENERGY AND DESALINATED WATER LOCATED IN ZARAGOZA (SPAIN)

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1 The model of the plant on TRNSYS

The object of this thesis is the dynamic modeling of a tri-generation pilot plant located in Zaragoza (Spain) near the institute CIRCE (Research Centre for Energy, Resources and Consumption), used for the production of electric and thermal energy and desalinated water. The studied plant is tri-generative because, besides the production of desalinated water, is able to produce sanitary hot water combined with electric energy produced by PVT collectors field. The electric energy produced is used for feeding the electric devices of the plant (i.e. pumps), home electric demand or is stored into two batteries set in series. The model of the plant in TRNSYS has been decomposed in “macro”, a series of subsystems which include the adopted components (“types”) connected among them. For an easier understanding, subsequently, a description of the components and of their operation inside of the various macros is provided. The pilot plant has been modelled on TRNSYS with the objective to compare results of the simulation with the experimental data.

2 Solar Loop

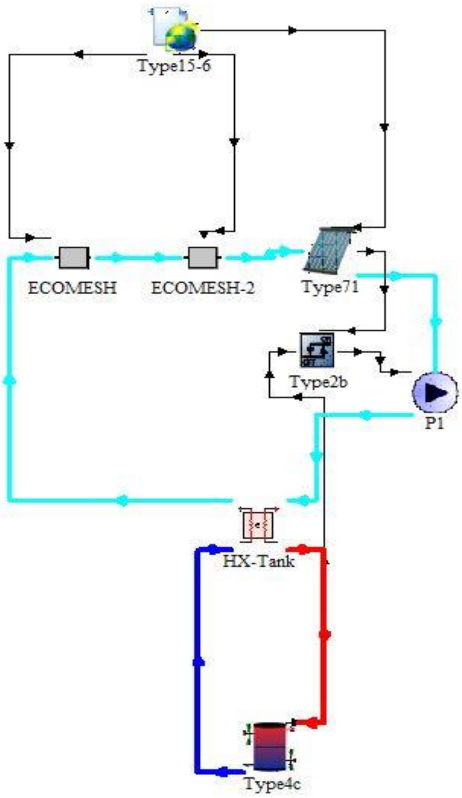

Figure 1 – Solar loop

The TRNSYS project starts with meteorological data from the place where the tri-generation system was located. In this case, Zaragoza city, located in the northeast of Spain, was chosen. Meteorological data were obtained from Meteonorm data base and has been introduced in TRNSYS as a file-input. Figure 11 shows the trend of solar radiation (40° tilt), wind velocity at WT (Wind Turbine) height (13 m) and ambient temperature along the year at Zaragoza, Spain.

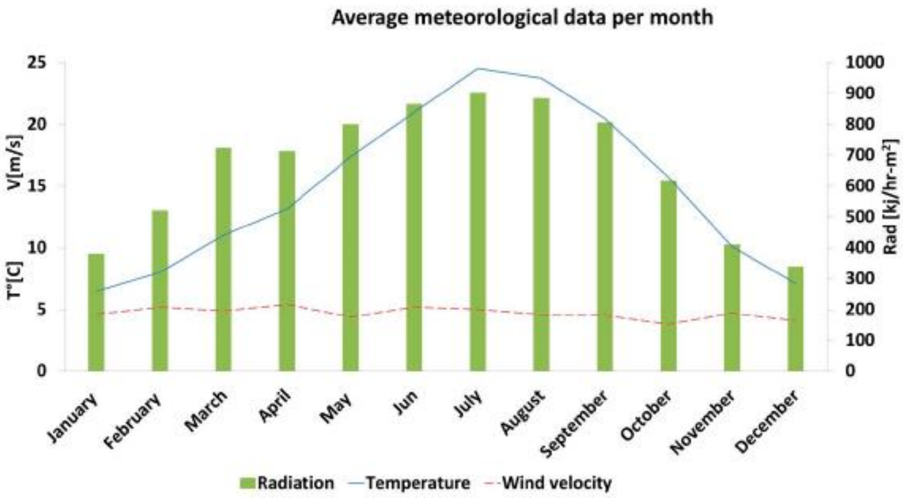

Figure 22 – Average meteorological data Zaragoza

The Solar Loop is made of 4 PVT collectors (1,63 m^2 each) and 1 evacuated tube collector ETC of 1.4 m^2. The PVTs are divided in two sets connected in series to the ETC such as in Figure 10. Each set of PVT is made of two collectors set in parallel. PVTs are connected to an inverter-battery system. PVTs and ETC collectors were linked to the meteorological input data (solar radiation, ambient temperature and wind velocity). They were also physically interconnected by means of a pump to a heat exchanger; through the hydraulic circuit the water/glycol (60%/40%) fluid is sent to the storage tank (Stratified Tank) by means of a heat-exchanger/pump system (HX Storage-Tank). A control system (Control 1) was connected to the pump, the tank and the ETC collector to induce a hysteresis cycle which allows the adequate regulation of the tank temperature. The solar energy which is not converted in electric energy is then turned in thermal energy.

3 Sanitary Hot Water (SHW) Loop

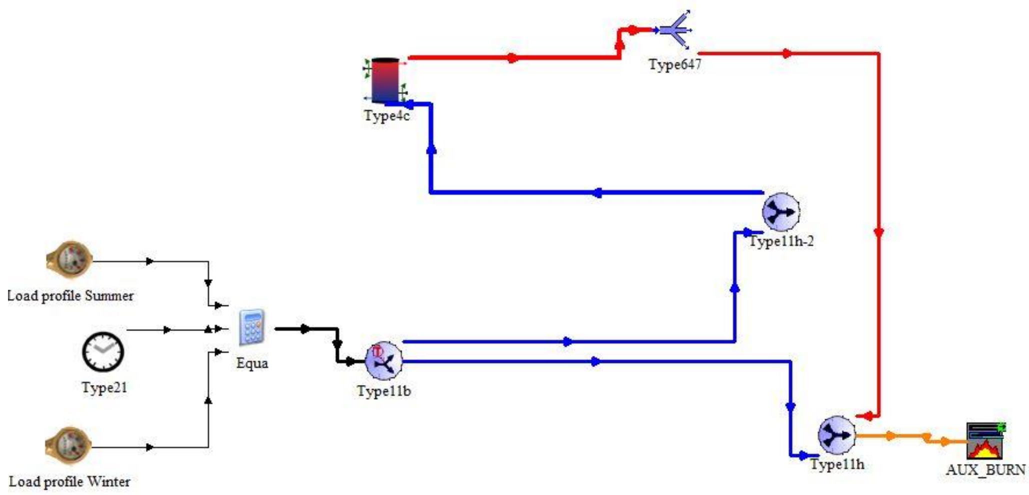

Figure 3 – Sanitary Hot Water loop

The hot water tank has a volume of 325 l and is fed with tap water by the Tempering Valve. The hot water from the Solar Loop is sent to the heat exchanger located in the Stratified Tank. According to the temperature to which water is heated in the Tank and to the demand of sanitary hot water, there are two valves (Type11b and Diverter type 647) that split the flow of hot water to the user and, when the temperature of the fluid is above the 58 °C to the MD. The temperature to which is served the SHW must not be above 45°C, and if it is lower than this value the thermal energy provided by an auxiliary heater (after Type11h valve), is used to raise up to 45°C. The Tank is also linked to the Tempering Valve, that has two functions:

- to feed the tank with tap water; in fact, if the SHW is drawn out from the tank and given to the user the same quantity of cold tap water must be refilled to the tank;
- to mix the SHW coming from the tank with a temperature above 45°C with cold running water.

4 Membrane Distillation (MD) Loop

When the temperature of the tank ranges between 58°C and 90°C, part of the hot water is sent to the heat exchanger (HX-Tank/MD) that supplies the MD unit and which therefore activates the distillation of sea water. The MD loop is divided in two sub-systems:

- From the storage tank side (hot loop) there is a pump (Pump 2) and a heat exchanger (tank-MD) that allows transferring the heat from the hot water tank to the PGMD (Permeate Gap Membrane Distillation) unit;
- On the other side (cold loop), the MD sub-system is connected to the same heat exchanger by means of a pump (Pump 3).

The heat exchanged allows maintaining the vapour pressure difference to vaporize and then to distil some seawater in the MD module.

A sea water tank feeds the MD unit every time the distillation process has been adopted.

Since in TRNSYS library a type which models the MD unit is not included, a new model has been created by Excel and connected to TRNSYS environment. This is based on the modelling and experimental tests of a commercial PGMD module, which is practically the same as projected in the pilot unit.

The PGMD contains a spiral wound desalination membrane with a total exchange area of 10 m^2, a length channel of 3.5m, a total height of 0.7 m, and a mean channel thickness of 3.2 mm. Design capacity of this MD module is 150 L/d, being its production peak around 20 L/h at rated thermal conditions (70°C of Tin in the evaporator). Operation of the PGMD module is presented in the next Fig.

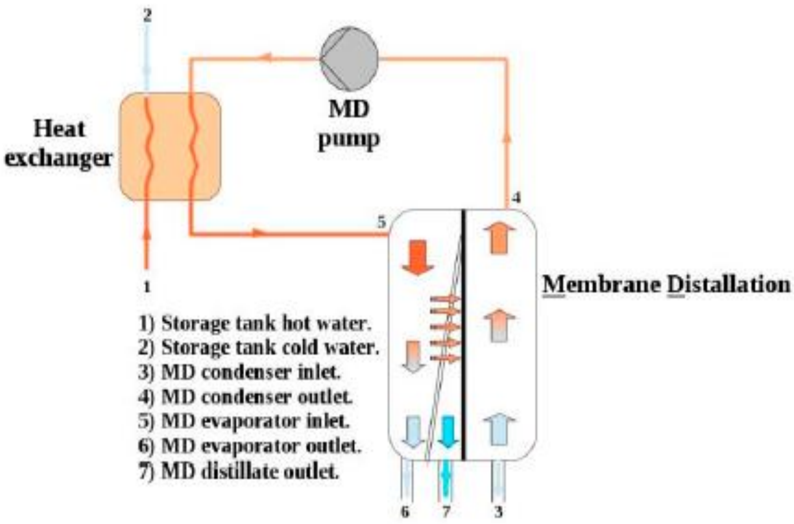

Figure 2. MD basic principle of operation.

- Cold sea water enters in the condenser (flow 3);
- Through the condenser path, cold sea water increments its temperature due to the heat exchange with evaporator and distillate channels (flow 4);
- Sea water is heated (flow 4) by an external heat exchanger (tank-MD) (flow 1-2);
- Hot sea water enters into the evaporator (flow 5). Here, some vapour is produced and the remaining liquid transfers the heat to the condenser side;
- Vapour passes through the membrane and then it is condensed to obtain the distillate (flow 7);
- Salinity of the remaining sea water is then slightly increased (flow 6).

5 Reverse Osmosis (RO) Module

This module has not been simulated in detail as a new model-type in TRNSYS, but only considering that its steady performance: a required DC power consumption equal to 110 W and an estimated production of 35 l/h of desalinated water. The technical features of the modelled RO unit are presented in the next table.

Table 1 – Reverse Osmosis parameters

Description	Characteristic Value
Nominal feed water salinity	35,000 ppm
Nominal temperature	25 °C
Fresh water production	35 L/h
Quality of water produced	300 ppm
Salt rejection	99.14%
Power consumption	110 W

6 Power loop

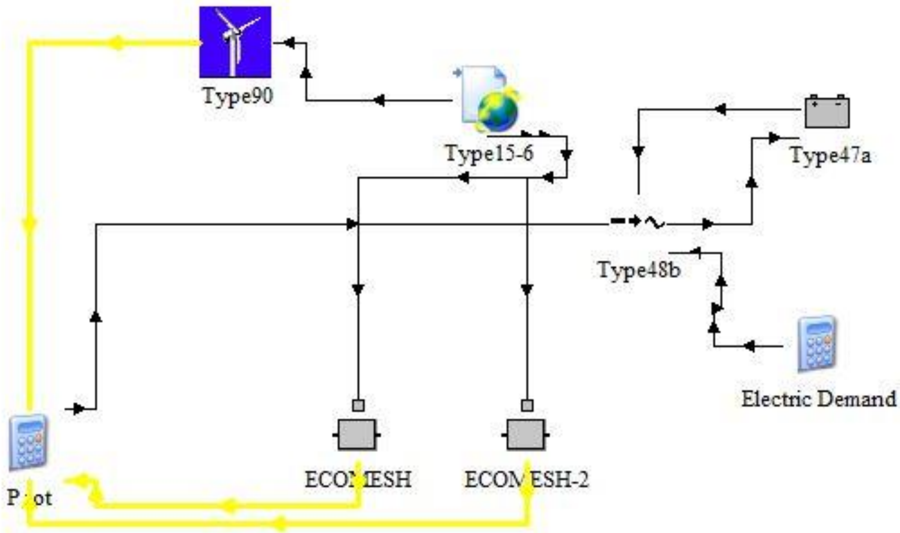

Figure 5 – Power loop

Power generated in the PVT sub-system is sent to a regulator which manages the charge and discharge of the battery. The WT 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 electric energy produced by WT and PVT collectors for further needs. Electric demand consists of the power required by two 5 W AC pumps (pump1 in the solar loop, pump 2 for the hot water to MD heat exchanger), by one 10 W DC pump used by the MD loop, and finally the power consumed by the RO module (110 W, DC). Any remaining power could be used to partially cover the domestic power demand or stored in the batteries. Daily electric demand for a typical dwelling was simulated according to standards. The next Table shows the monthly electric demand for a typical Spanish family home as well as the average energy consumption per day implemented in TRNSYS simulation.

7 Model Validation

In order to validate simulation model of the plant developed in TRNSYS environment, a comparison has been performed between experimental data about Solar Radiation, Temperature inlet and outlet of PVT, ETC, MD, Tank, Distillate production furnished by Zaragoza University in a particular summer day (September 8^{th} 2017), and results from simulation in the same day. This day has been chosen because it was a day with a very stable radiation profile all day long, no cloudy, and a day with about nine hours of continuous distillate production from MD.

8 Comparison

The simulation for this day has been performed with a time-step of 1 minute and begins at 10:00 a.m. and ends at 19:00 p.m. At first a comparison has been led between the outlet temperatures from the solar loop, i.e. the outlet temperatures from PVTs and ETC.

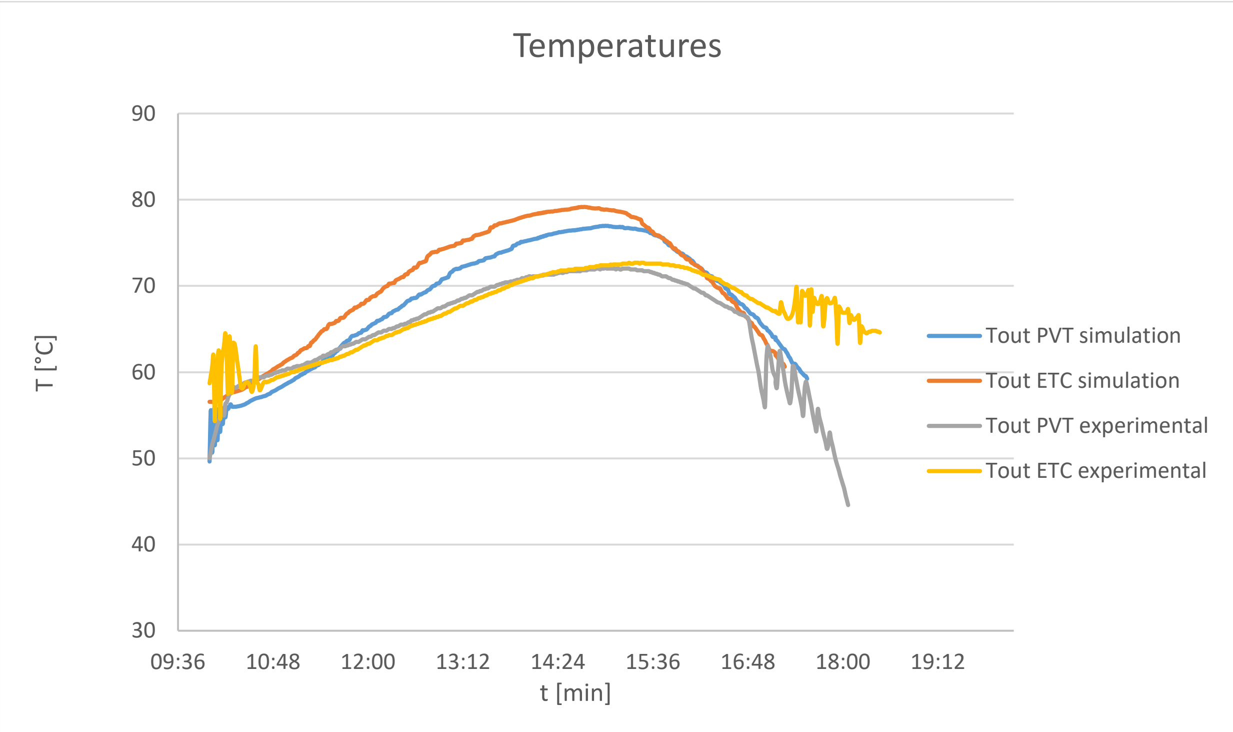

Figure 6 – Plot of temperatures outlet from ETC and PVT

For each comparison the relative average percentage error [%] has been calculated as follows:

$$\varepsilon = \frac{Tsimulation - Texp}{Texp} * 100$$

$$\bar{\varepsilon} = \frac{\sum \varepsilon}{N}$$

with N=number of time steps

These average errors are obtained:

$\bar{\varepsilon}$ **PVT [%]**	$\bar{\varepsilon}$ **ETC [%]**
- 1.25	- 1.80

Then the same comparison has been led between the distillate production from the Membrane Distillation in experimental data and in simulation, and the same percentage error has been calculated:

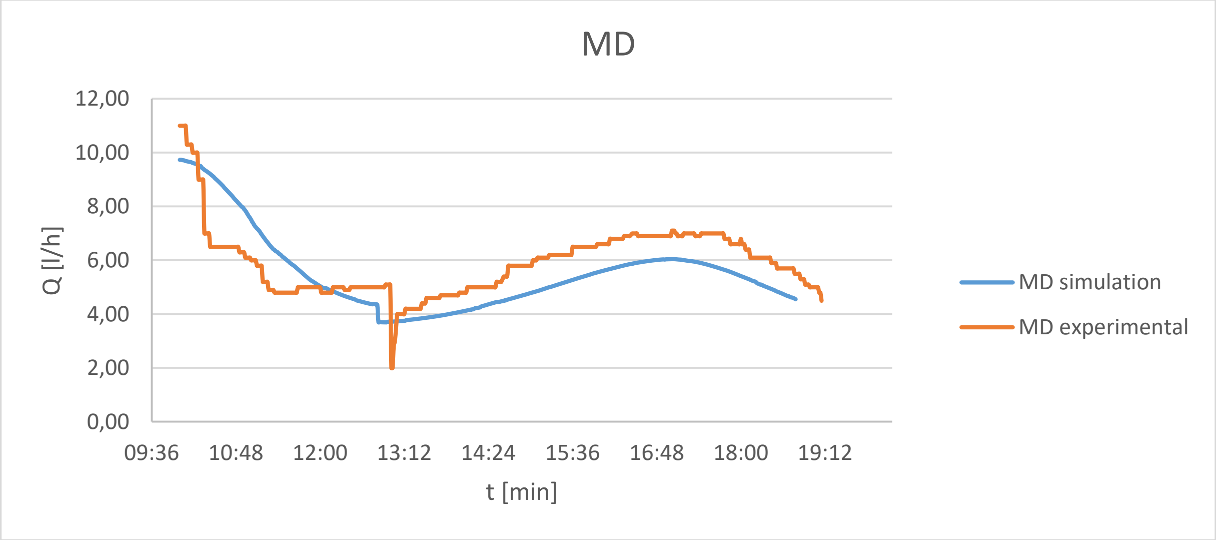

Figure 9 – Plot of MD distillate production

$\bar{\varepsilon}$ **distillate MD [%]**
6.30

Finally, the same operation has been performed for the outlet temperature from the condenser T_{cout} (inside MD) and inlet temperature in evaporator T_{ei} (inside MD):

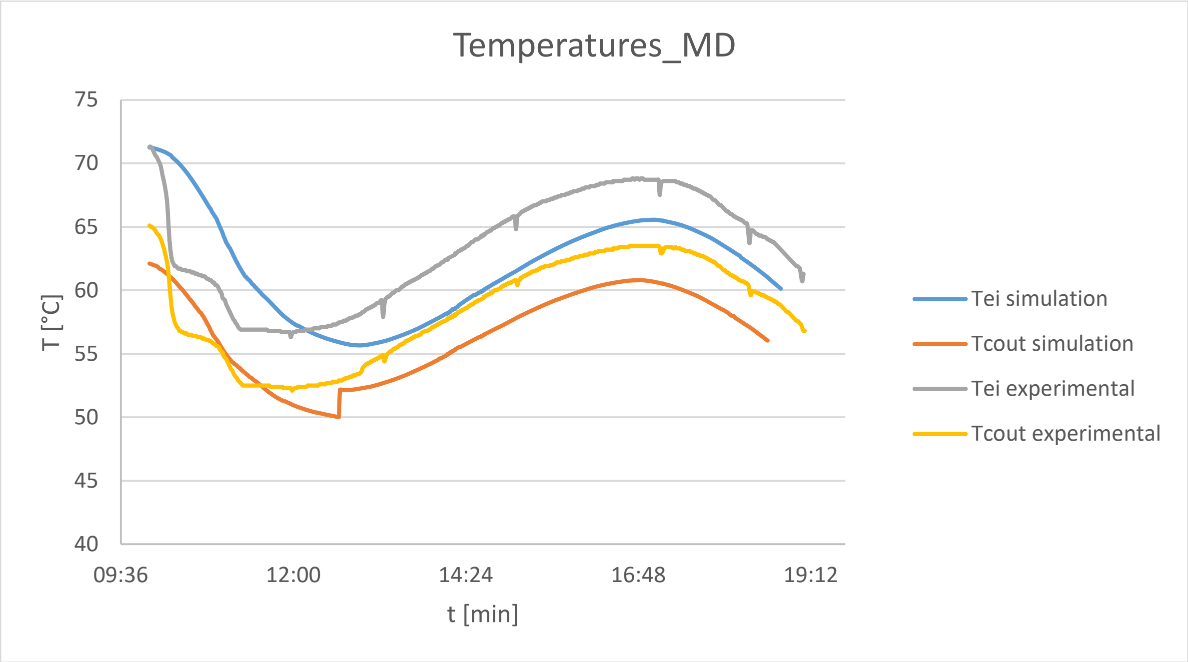

Figure 103 – Plot of Temperatures at Evaporator inlet and at Condenser outlet

With these errors:

ε̄ Tei [%]	ε̄ Tcout [%]
3.20	4.00

In the end, with these percentage of errors is possible to state that the process of model validation has given good results, and that is possible to deeply analyze the behavior of the components in the plant in various scenarios using the TRNSYS model.

ε̄ T PVT [%]	ε̄ T ETC [%]	ε̄distillate MD [%]	ε̄ Tei [%]	ε̄ Tcout [%]
- 1.25	**- 1.80**	**6.33**	**3.20**	**4.00**

9 Daily simulation

To better understand the variations of the quantities involved, we proceed to analyse the daily simulation results. The time step chosen is of 1 hour for each simulation. Representative summer and winter days have been chosen to show the operation of the plant at different condition.

10 Typical Summer Day

The first analysed day of simulation is August 19th , which begins at 5544th hour of the year and ends at 5568th hour of the year. The production of distillate from MD is active from about 13:00 to about 20:00, before and after this period of simulation is not active because the incident radiation is too much low and the outlet temperature of the hot water from the tank is lower than 58°C ("Upper Dead Band" in the differential controller for the MD loop). However, the RO is always active, because its operation is obviously not dependent from the solar thermal loop.

The analysed plots show the hourly trend during the day of the following temperatures:

- **T ETC**: outlet temperature of water/glycol solution from the ETC;
- **T PVT**: outlet temperature of water/glycol solution from the PVTs;
- **Tm tank**: average temperature of the water in the storage tank;
- **T load tank**: outlet temperature of the hot water from the storage tank;
- **T refill tank**: temperature of the cold water refilling the storage tank;
- **T SHW**: temperature of SHW to the user;

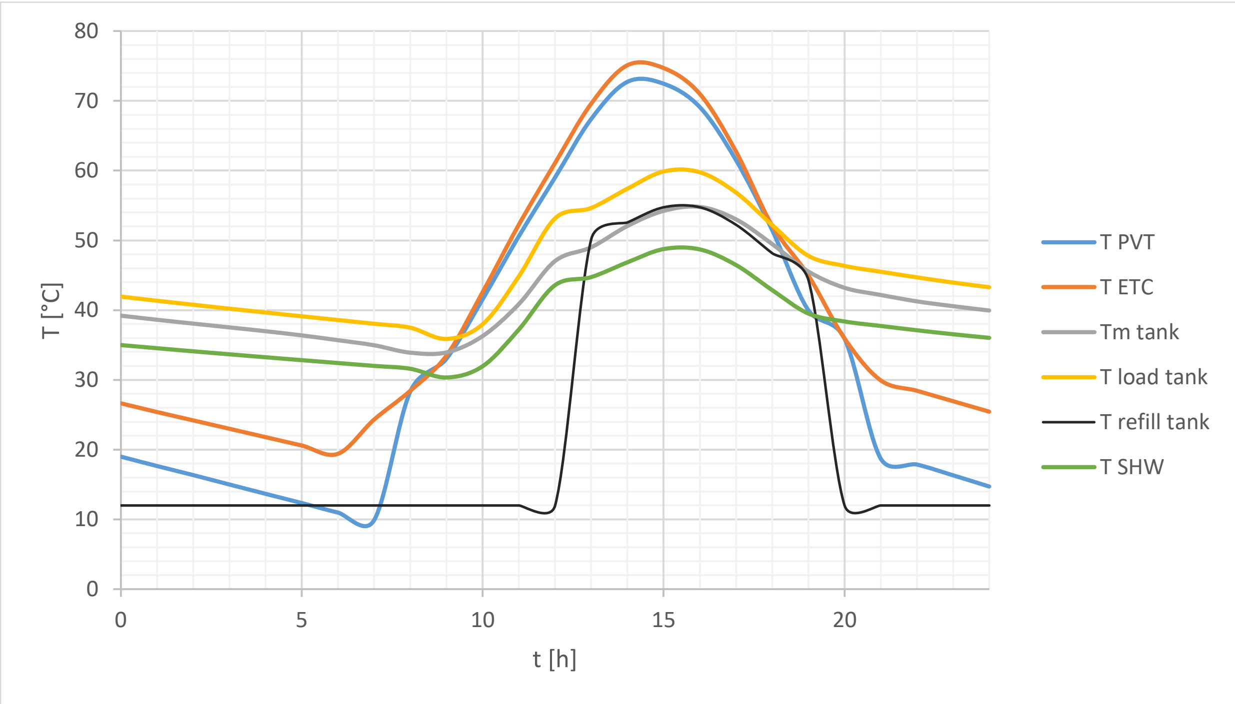

Figure 4 – Temperatures plot of a typical summer day

Outlet temperature from collectors during the day reaches a peak of 75°C and allow to activate the MD loop and SHW loop. Obviously, "T ETC" is greater than "T PVT" during all day and this can be noticed by the plot. During the simulation "Tm tank" is between 55°C and 40°C, while it can be noted that "T refill tank" starts from 12°C, temperature of the tap water during this period of time in Zaragoza, then grows till 55°C because is mixed with hot water coming from HX-tank/MD because of the activation of solar and MD loop. It is possible to see that “T SHW” during the day is almost always lower than 45 °C, for this reason an auxiliary heater has been expected to raise up “T SHW” at 45°C.

The same analysis has been done for the Power generated, demanded, Heat rate produced and exchanged, Fresh water production and Control system.

11 Typical Winter Day

The typical winter day chosen for the simulation study is February 27th, which begins at 1392th hour and ends at 1416th hour of the year. The solar radiation in this day allows to produce SHW, to cover electric demand for about seven hours and to produce desalted water from the MD for about four hours. The most significant period in this day of simulation is from 8:00 to 19:00, before and after the solar radiation is very low or nearly zero and the components of the plant can’t operate.

Outlet temperature outing from panels during the day reaches a peak of 68°C around 16:00 and let the tank to activate the MD loop and SHW loop. It is possible to notice that before the 8:00 and after 20:00 p.m. “T ETC” and “T PVT” are very low (lower than 0°C) because of the solar radiation that is nearly zero and because we don’t have any flowrate flux. During the simulation “Tm tank” is between 25°C and 50°C, and, “T refill tank” starts from lower value than that of summer day (6°C). It is possible to see that “T SHW”, except for 3 hours is always 45 °C so the auxiliary heater has to be activated. Subsequently the Temperatures plot:

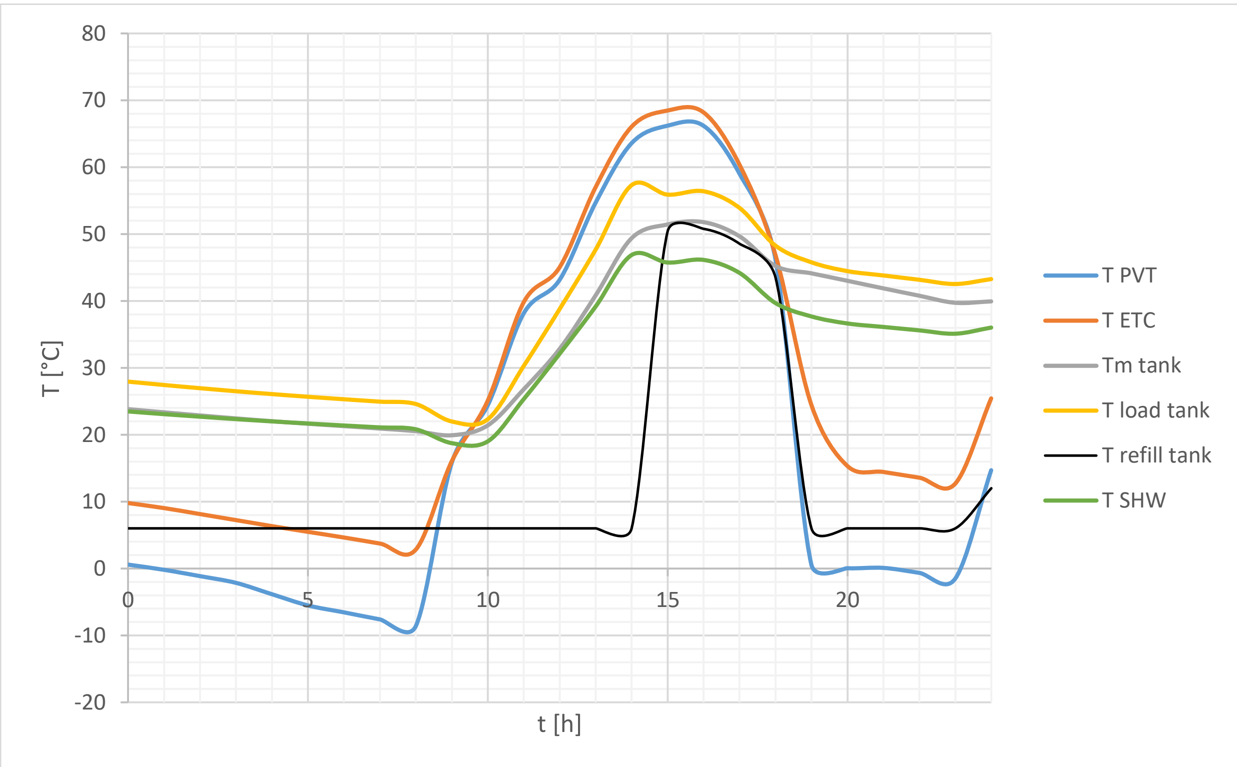

Figure 125 – Temperatures plot in a typical winter day

Such as for the typical summer day, the same analysis has been done for the Power generated, demanded, Heat rate produced and exchanged, Fresh water production and Control system.

The results of the annual simulations are summarized in the table 13:

Table 3 – Results of annual simulation

Parameters	Value	Unit	Parameters	Value	Units
I_{tot}	3.72E+07	kJ/anno	**Q_{HX-MD}**	7.18E+06	kJ/anno
$P_{gen\ tot}$	5.30E+06	kJ/anno	**Q_{ETC}**	1.75E+06	kJ/anno
$P_{from\ grid}$	4.12E+06	kJ/anno	**Q_{PVT}**	1.73E+06	kJ/anno
$P_{dem\ tot}$	7.93E+06	kJ/anno	**$Q_{d\ MD}$**	5.26E+03	L/anno
$P_{dem\ house}$	5.42E+06	kJ/anno	**SHW_{dem}**	3.73E+04	L/anno
$P_{dem\ pumps}$	9.83E+04	kJ/anno	**SHW**	3.73E+04	L/anno
$Q_{HX-tank}$	5.27E+06	kJ/anno	**Q_{RO}**	4.41E+05	L/anno
$Q_{HX/MD-tank}$	1.12E+06	kJ/anno	**FW_{demand}**	1.06E+05	L/anno

Where we have:

Table 4 – Coverage ratio

Product	Production	Demand	Coverage Ratio
SHW	37.3 m^3/year	37.3 m^3/year	100%
Fresh Water (MD+RO)	446 m^3/year	106 m^3/year	420%
Electricity	1472 kWh	2200 kWh	66%

FW production is higher than the demand. Thus, the RO unit should be partly turned off at night, or alternatively some amount of water could be sold or stored for further peak demands.

12 Parametric Analysis

Following a parametric analysis has been led with the purpose to observe different working condition from that of reference, to understand the effects of the variability of some significant parameters of project on other representative indicators of the energetic, economic and efficiency conditions of the proposed system. The parameters chosen for this analysis are presented in the next table.

Table 5 – Parametric analysis table

	Interval of Variation	Reference Value	Unit
ETC area	1.4-5.6	1.4	m^2
Num PVT	4-7	4	-
Num WT	1-4	1	-

13 Economic Analysis

In order to better analyse results of parametric analysis from an economic point, a study about plant costs of investment and of exercise has been also led. On two different configurations of the plant studied it was chosen to focus: plant where Fresh Water is produced from RO; plant where is produced from MD. This choice is motivated by the coverage ratio of FW of 420% that doesn't explain the investment for both the desalination technologies.

Some simulations with TRNEdit has been led, the specialized editor for the creation or the change of input file, which let us to make comparison between the different conditions of working and that one of reference.

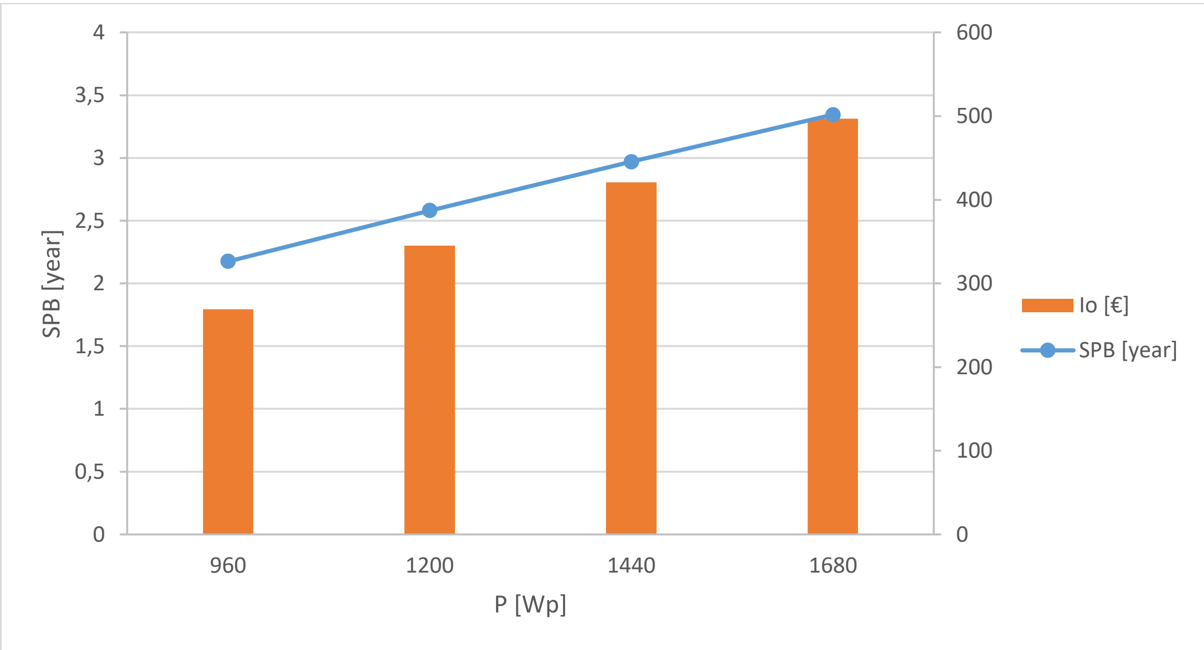

Figure 13 – Economic analysis on the variation of PVT area in MD configuration

This plot is about a plant with MD and has been lead an analysis on the variation of the number of PVT panels, as can be seen from the Power produced “P” that grows. “Io” is the initial capital cost of the plant reduced by a government economic incentive for the construction of a plant of renewable energies. “SPB” is the Simple Pay Back period, refers to the period of time required to recoup the funds expended in an investment, which is calculated as:

$$SPB = \frac{Io}{DC}$$

Where *DC* is the difference between the exercise costs in the reference condition and in the plant configuration proposed.

As number of PVT grows, also power generated grows, so power required from the grid is reduced, and *DC* grows; but in this case Io grows greater than DC so SPB starts from 2.2 years in the reference condition and then reaches around 3.3 years with the growth of the number of panels.

The next plot is about a plant with RO, and the parameters analysed are always SPB, Io and P. It is important to specify that Io for the RO plant has been characterized by an incentive lower (10 k€ lower) than that one of the MD plant (15 k€). In this configuration we don’t need to buy fresh water, because the ratio coverage is around 300%, but the electric power bought from the grid is greater because of the RO. The SHW costs are practically constant.

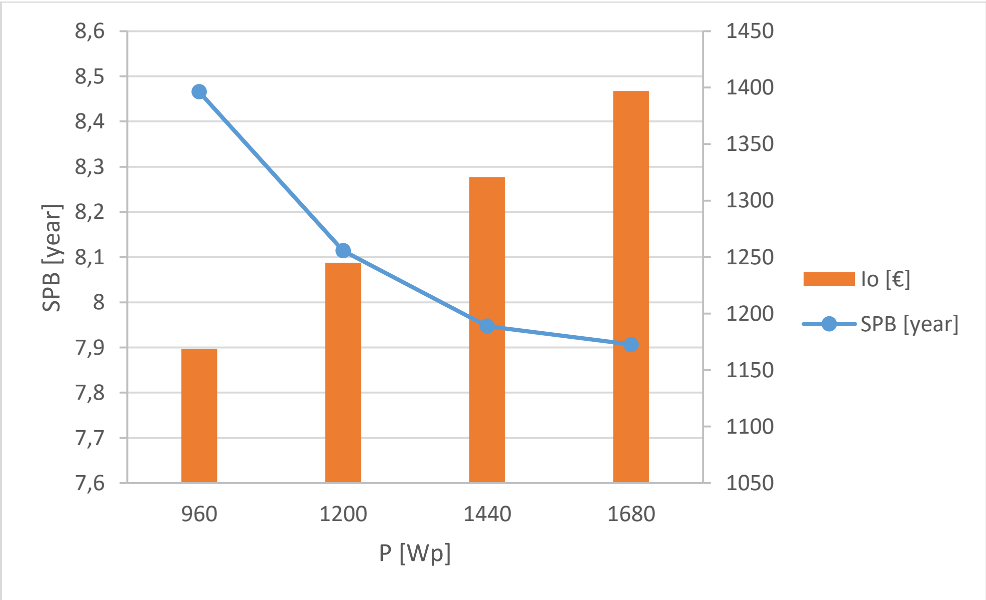

Figure 14 - Economic analysis on the variation of PVT area in RO configuration

In the next plot the SPB in a RO plant through the variation of the ETC panel area has been analysed.

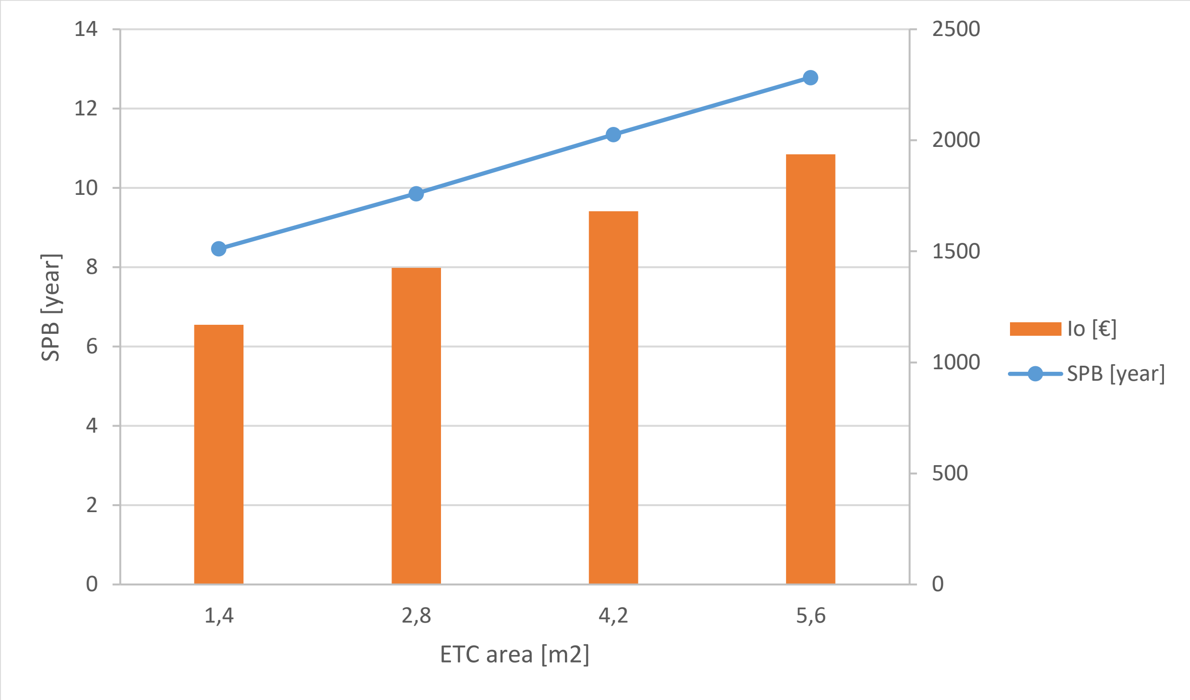

Figure 15 - Economic analysis on the variation of ETC area in RO configuration

As it can be seen SPB grows from the reference condition with an ETC of 1.4 m^2, and from 8.5 years goes to 12.7 years. The reason is that DC is increased lesser than Io, because the reduction of the energy that the auxiliary boiler needs to heat the SHW is not so relevant with the growth of the ETC area.

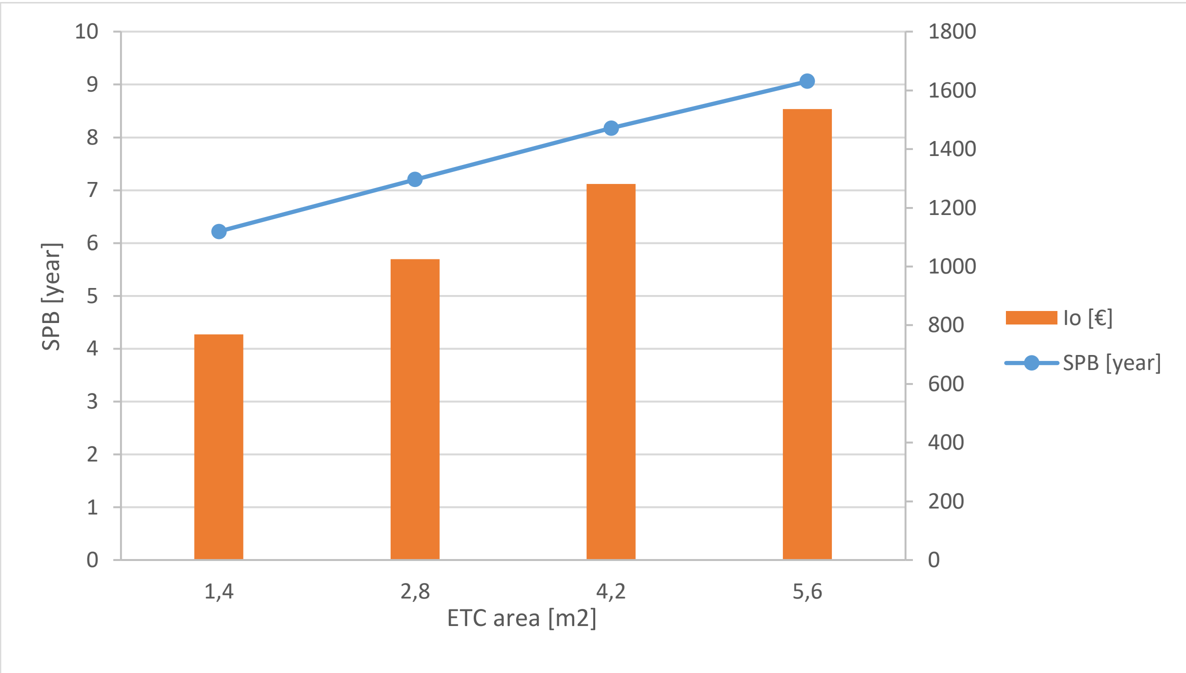

Figure 16 - Economic analysis on the variation of PVT area in MD configuration

In the previous one plant SPB grows with ETC area and when the area is 4 times that of the reference condition reaches a value of 9 years. This is due to the DC that grows lesser than Io, and the reason are the Sm^3/year of natural gas that the auxiliary boiler needs to heat SHW that doesn't decrease too much with the growth of the ETC area.

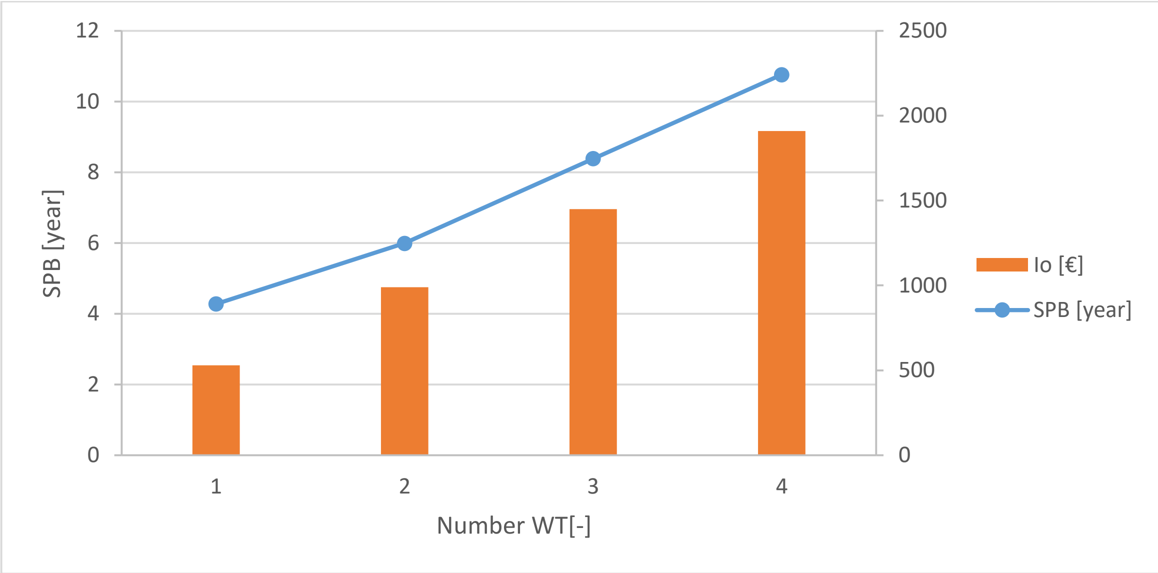

Figure 17 - Economic analysis on the variation of WT number in MD configuration

In the previous plot it is possible to see the trend of SPB increasing the number of WT until 4 in a MD plant configuration. The electric energy consumption decreases, but lesser than Io. In the next plot is seen how in a RO configuration plant despite the reduction of the electric costs, with the increment of the number of WT also grows the period of time in which will be a return of the initial investment. But it is important to remember that even though SPB values in both plant configurations are similar, the MD plant is characterized by greater initial capital costs and incentive.

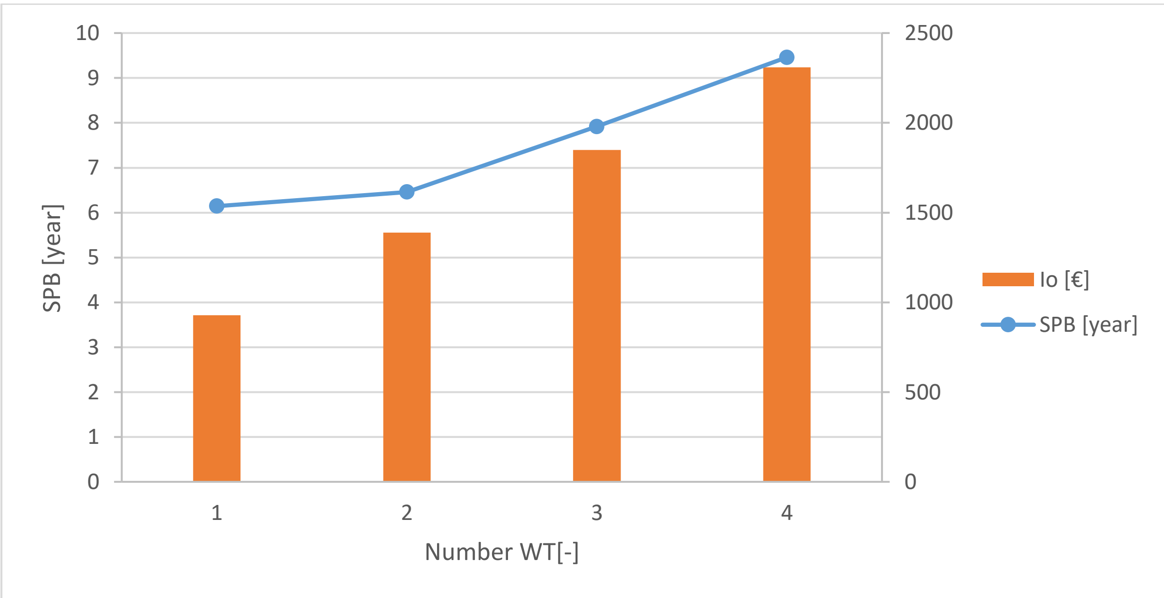

Figure 18 - Economic analysis on the variation of WT number in RO configuration