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Master’s degree in Energy and Nuclear Engineering
Renewable Energy Systems

Solar Thermal Technologies Project

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Summary

INTRODUCTION
The project consists in exploiting the software POLYSUN in order to simulate the installation of solar collectors that have to provide domestic hot water for a building.

- Initial Input Data

The chosen location is Barcelona (ES), a warm site known for its good weather that can exploit to the best the potential of the solar collectors, however the high temperatures of this city in summer can also lead to stagnation phenomenon. As a conclusion we can say that to install the plant in such a heated location may not be the best choice due to this circumstance, but we will further analyze the stagnation phenomenon in the following paragraphs.

For Barcelona we have:
- Latitude=41.42°
- Longitude=2.17°
- Altitude=121 meters

Other provided data are:
- Number of people=30
- Temperature needed for DHW=45°C
- Daily hot water demand=50 liters per person

- Model Setup

In order to complete the project setup we need to choose three different solar collectors from the software's catalogue in this way we can compare them and choose the best in terms of performances and price. Two of the collectors are flat-plate type, one is a low quality and the other a high quality, while the third is a vacuum tube type.

The difference between flat plate and vacuum tube collectors is that in the last technology the tube in which the heat carrier fluid flows is surrounded by an outlet glass tube, between the two tubes there is the vacuum. This configuration allows us to reduce convective losses through the environment so we can reach higher efficiencies but is also more expensive.

The main guideline to follow in the choice of the collectors is the transmittance value, which represents the ratio of the light energy hitting a body to that transmitted through it. A good collector transmits a lot of energy with respect to the energy that strikes it, so the denominator is high with respect to the numerator and the ratio is low. On the contrary low quality collectors do not transmit so much energy and their transmittance is higher. We can say that for an high quality collector the transmittance is between 3 and 2, while for a low quality collector the transmittance value is between 5 and 6.

Therefore the chosen collectors are:
- High quality: INTEGRO 25 VI
- Low quality: Solarkollektor
- Vacuum Tube: HCM15-58/1800

For the high quality solar collector the transmittance value is 2.00, for the low quality is 6.08 and for the vacuum tube we have chosen a collector with a transmittance of 2.01.

After choosing the solar collectors and the boiler the setup, the system is complete as shown in figure 1:

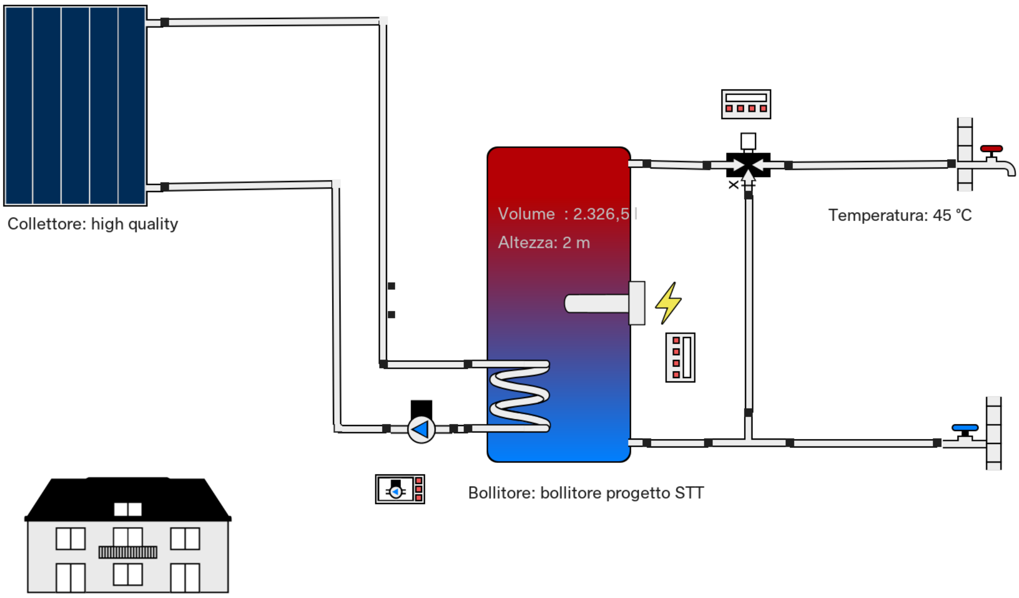

Figure 1 - System layout on POLYSUN

PART 1

STEP 1
The first step consists in calculating the Solar Fraction (SF) and the Solar Yield (SY) for the system.

The solar fraction can be defined as the energy provided by the collectors divided by the total energy required which is the one provided by the collectors plus the energy given by the auxiliary.
The solar yield instead refers to the power produced by the collectors divided by their area, so it gives us the measure of how many watts of power we can produce from a meter square area of collectors.

The input data for this step are:
- Solar collector area=30 m^2
- Tank volume=1500 litres
- Orientation=0°
- Tilt angle=ϕ-15° where ϕ is the latitude of our location

Since the collectors have a specific surface, to keep the number of collectors an integer (because it is not possible to split the collectors), we had to work with values of area that are a bit different from the input one but we stayed as near as possible to the value of 30 m^2.

While the solar fraction is automatically provided by POLYSUN, the solar yield has to be calculated as:

$$SY = \frac{Qsol}{Ac}$$

The obtained results are summarized in table 1:

Table 1 - SF and SY with 30 m^2 of solar collector area

model	number of collectors	gross area	aperture	Qsol	Qaux	SF	SY
		m^2	m^2	kWh	kWh	%	kWh/m^2
LQ	15	30,75	27	14844	5966	71,3	483
HQ	24	29,76	26,02	18066	3032	85,6	607
VACUUM	13	30,56	18,12	16480	4562	78,3	539

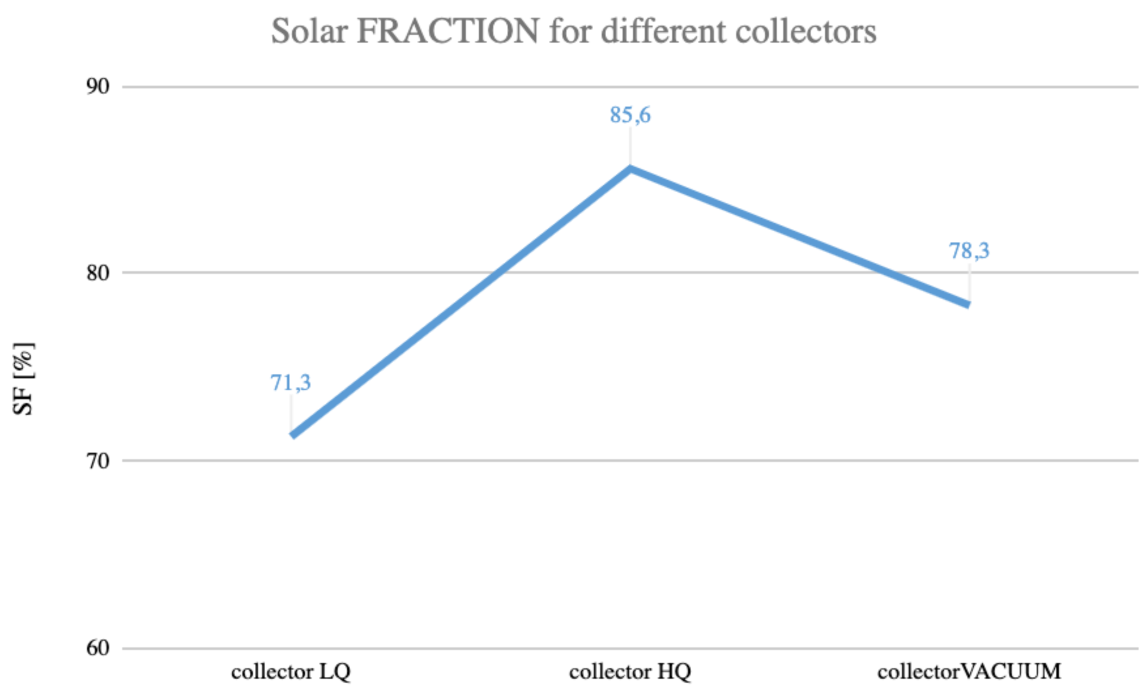

Figure 2 - Solar Factors for different collectors

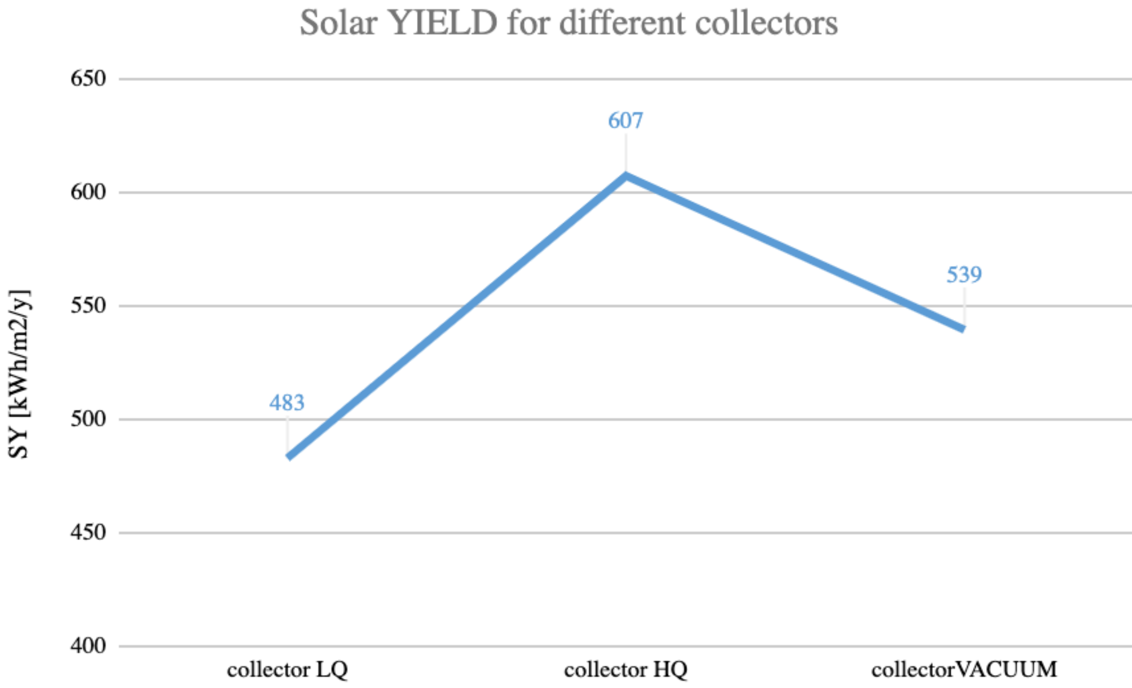

Figure 3 - Solar Yield for different collectors

As expected the values of SF and SY are relatively high, for example usually the solar factor stays between 50-60% instead we arrive at 78% and 85% for the best collectors, this is because of the very sunny location we have chosen, in fact we know that latitude and weather have a lot of influence on this parameter. (Figure 2, Figure 3)
We can also notice that the low quality collector has a lower value of both SF and SY if compared to the high quality and the vacuum tube collectors, so its performances are not that good.
We could expect better performances from the vacuum tube but we also know that it is particularly advised for cold, cloudy weather so to install this kind of collector may not be the best strategy in this case.

STEP 2

Solar factor is a function of the collector area: it represents the percentage of solar source exploited by the system. We perform the parametric analysis of the SF with respect to the solar collectors area. The solar collectors are not independently connected to the system, but they should be considered as a solar loop.

The power that is transferred to the storage is depending on how much power can be exchanged in the heat exchanger. The storage is the real part of the system where we receive the power of the solar system and the power of the auxiliaring. In order to increase the solar power to the storage, we increase the flow rate in the loop.

So we choose 5 values of solar collector area with an integer number of solar collectors in the 40-80% solar fraction range. We change the coil heat exchanger size in the tank in order to keep the same solar collector area to heat exchanger area ratio. We take note of Qsol, Qaux, Solar factor and Solar yield.
We choose different numbers of panels, these are the two graphs of solar fraction and solar yield (Figure 4, Figure 5) as a function of the gross area for the High Quality (HQ) collector, Low Quality (LQ) collector and Vacuum Tube (VT).

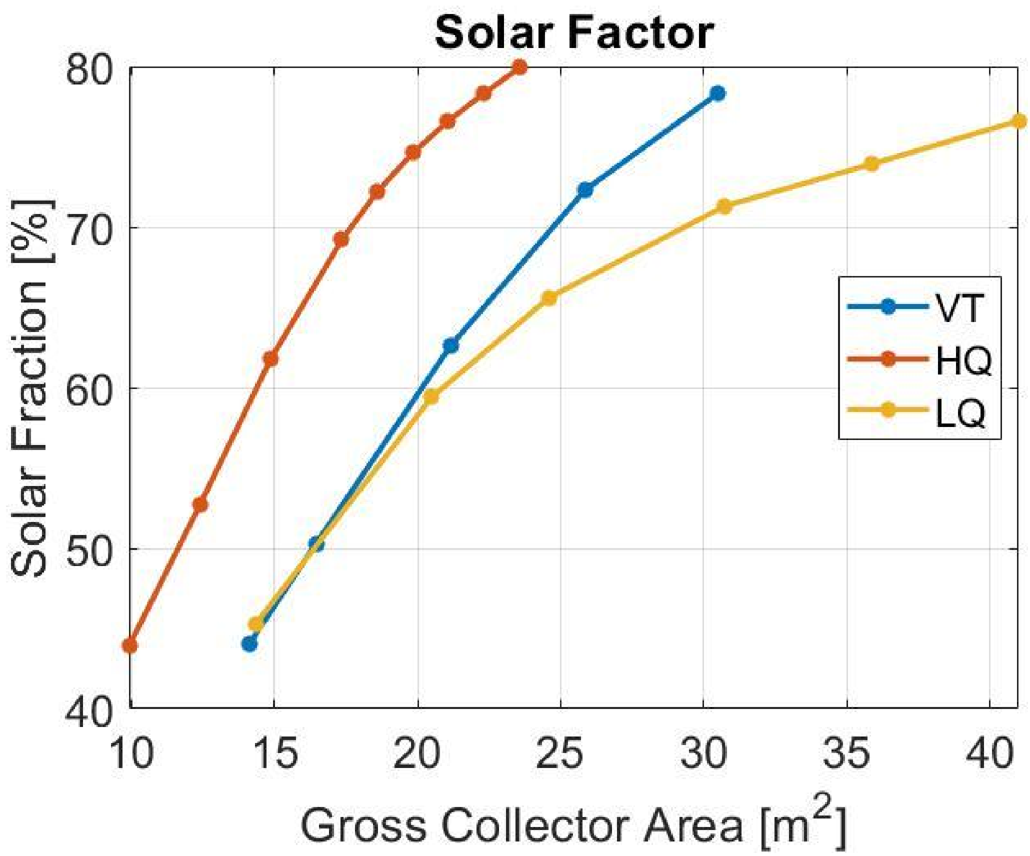

Figure 4 - Solar Factor with respect to solar collector area for different collectors

We can notice that at a certain point we reach a plateau. In fact for the SF graphs, even increasing the collector area, the SF does not rise more than 70% so any further addition in terms of collector area is a waste of money.

It is requested to find the value of the area in order to obtain a solar factor equal to 60%. This is a compromise between efficiency and economy.
Area for different collector

- Flat Plate (FP) inexpensive (LQ) collectors: Ac=20.8 m^2 , numbers of panels ~ 11
- Fp premium quality (HQ) collectors: Ac=14.39 m^2 , numbers of panels ~ 12
- Vacuum Tube (VT) collector: Ac=20.1 m^2 , numbers of panels ~ 9

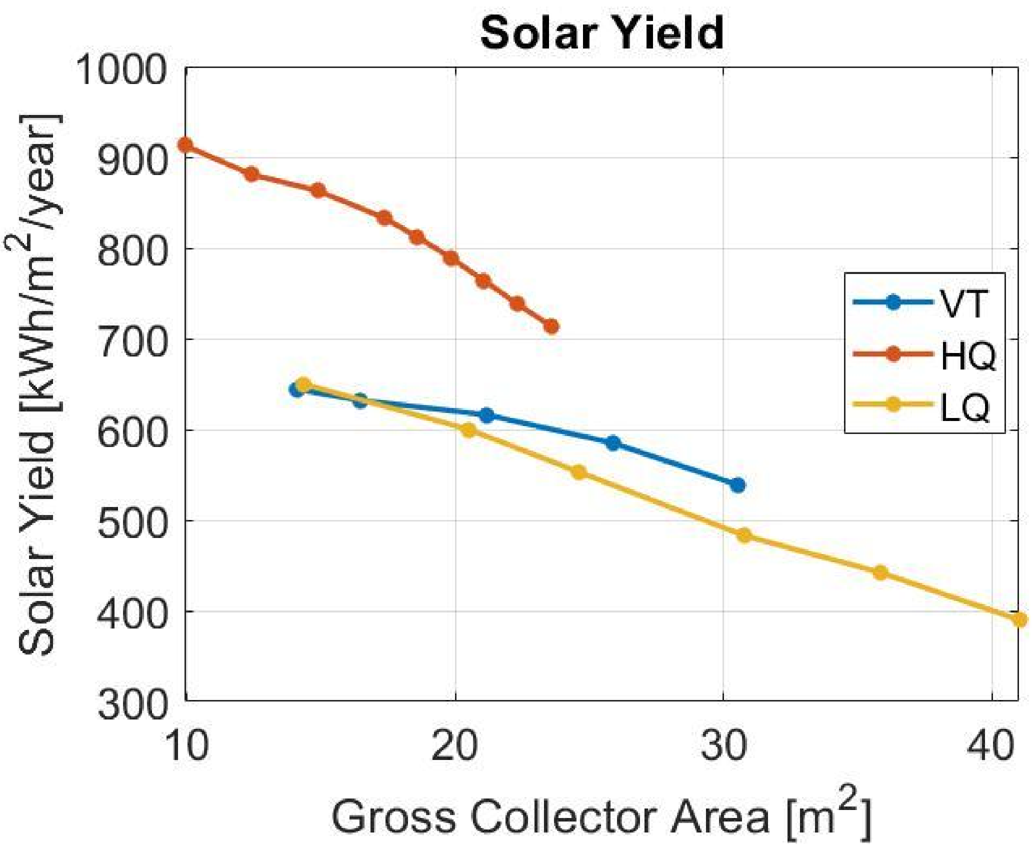

Figure 5 - Solar Factor with respect to solar collector area for different collectors

STEP 3

At this point we are requested to find the optimal tilt and orientation angle, in order to maximize the incident solar radiation and the energy production.
The solar azimuth angle,γs, is the angular displacement from south of the projection of beam radiation on the horizontal plane. Displacements east of south are considered negative and west of south are positive.
The tilt angleβ is specific for the site, it varies with latitude. The panel will collect solar radiation most efficiently when the sun's rays are perpendicular to the panel's surface.

In order to obtain the optimal tilt angle and the optimal solar azimut we set the value of area at 60% of the solar fraction found in point 2. We started by setting the solar azimuth to 0° and we varied the tilt angle between ϕ-15 ° and ϕ+ 30 °. We found the β value corresponding to the maximum solar fraction value by imposing the first derivative of the function equal to zero.

Proceeding step by step we fixed the optimal β value found and we recalculated the solar factor now by varying the γs values (between -45° and +45°) . Following the conjugate method, we have repeated those two steps until there was no further variation of those angles and we have come to these results. (Table 2)

Table 2 - Optimal tilt and orientation angle

	Optimal tilt angle	**Optimal orientation angle**
High Quality	37.2°	-5°
Vacuum Tube	36.1°	-2.8°
Low Quality	38.6°	-8.6°

These are the graphics at the last step of the procedure. (Figure 6, Figure 7, Figure 8)
Regarding the optimal tilt angle the obtained graphs are:

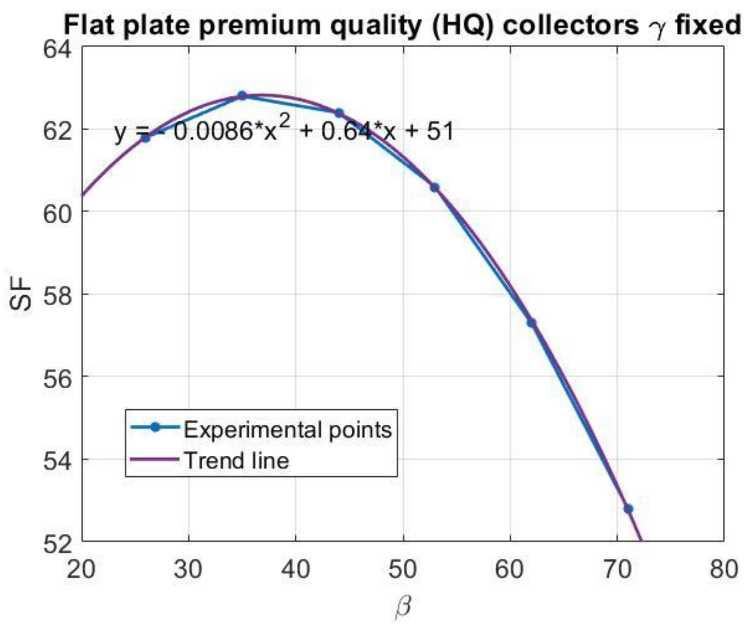

Figure 6 - Optimal tilt angle for HQ

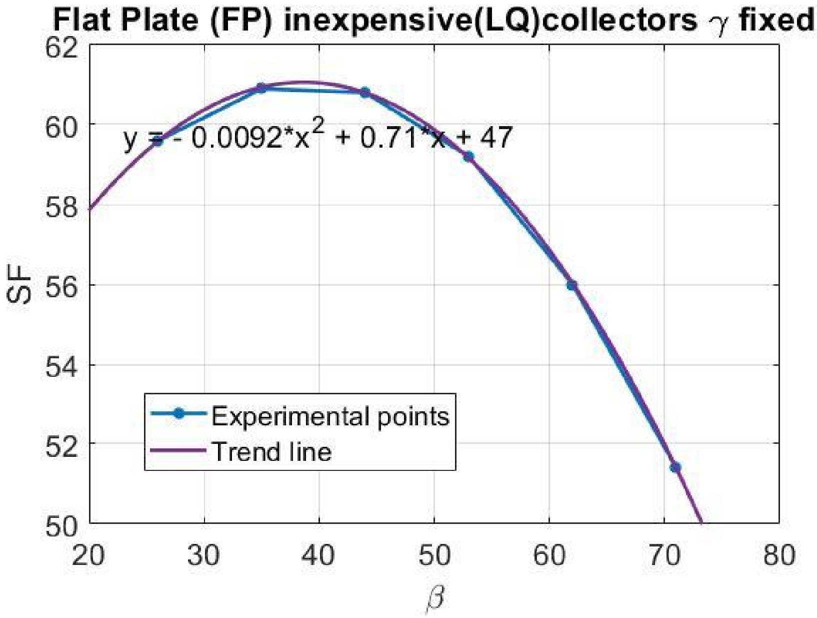

Figure 7 - Optimal tilt angle for LQ

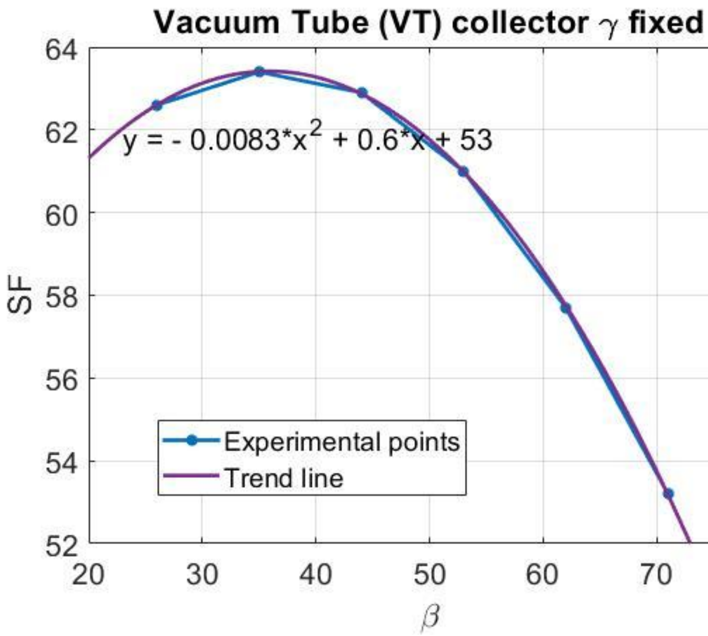

Figure 8 - Optimal tilt angle for VT

Regarding the optimal orientation angle, from the theory we expect it to be equal to 0°, which corresponds to the south orientation; in fact taking into account just the values of Qsol the maximum should be at 0° because the movement of the Sun is symmetrical with respect to the south.

The obtained graphs (Figure 9, Figure 10, Figure 11) instead show slightly different values:

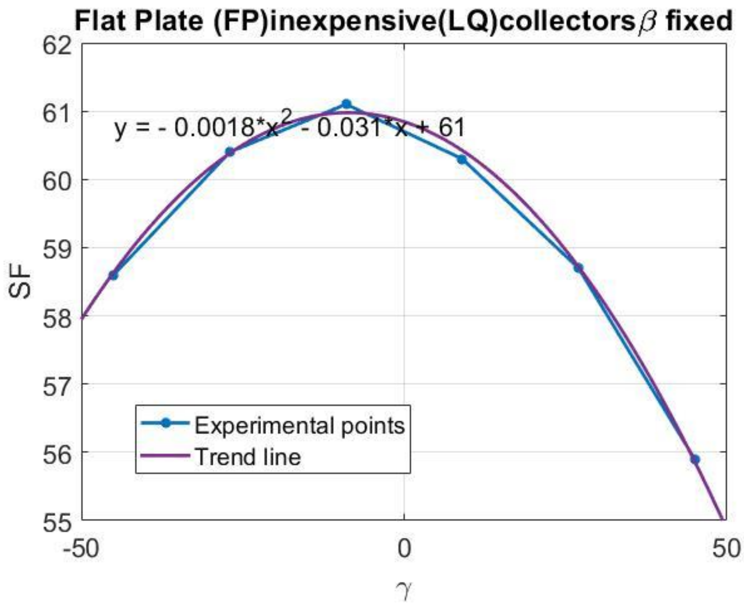

Figure 9 - Optimal orientation angle for LQ

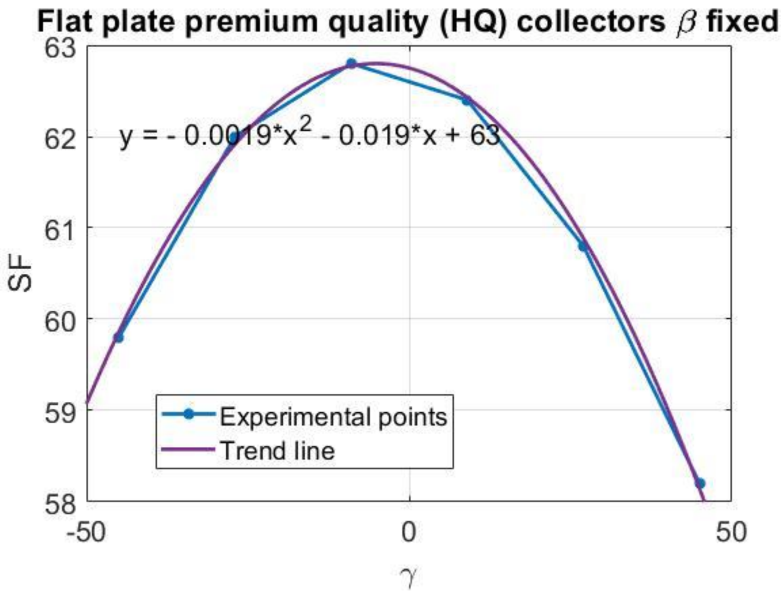

Figure 10 - Optimal orientation angle for HQ

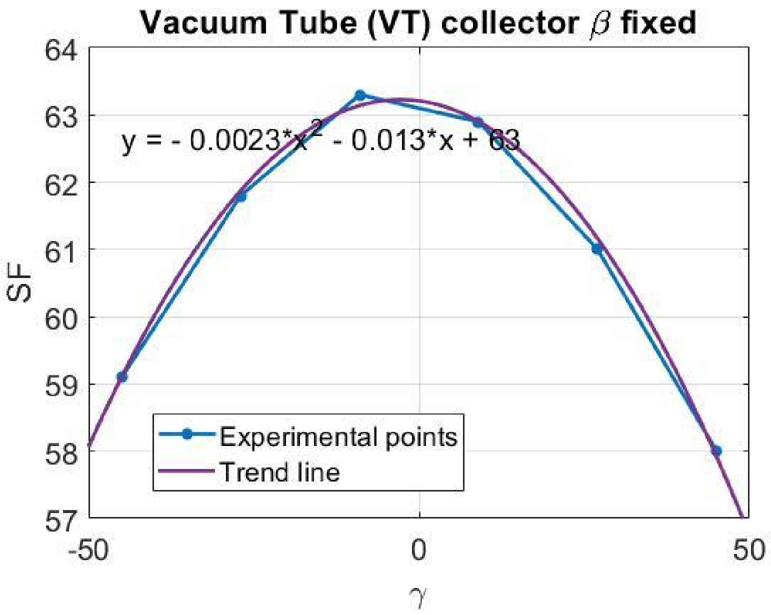

Figure 11 - Optimal orientation angle for VT

In the simulation we are obtaining slightly different values with respect to the theoretical ones, this is because the south orientation is the ideal optimal orientation but in the real world we have to take into account other factors like the weather, in particular clouds, or issues that can provide shading like mountains or hills. Furthermore, since we are obtaining negative values of the orientation angle, we can say that those factors are shifting our optimum towards east.

STEP 4

The purpose of the step is to evaluate the tank volume for each model of plant.
We start fixing the collector area at solar factor equal to 60%. In order to make a comparison between the different collectors, we consider the ratio of the volume over the collectors area: this value must be included between 50 and 200 lt/m^2. The ratio represents the feasibility of the different plants, in order to obtain coherent values of Solar Factor and Solar Yield. High tank volumes will mean high cost, but more potential to store energy.

Initially we set five values of volume, obtaining results for SF around 60%. We decided to investigate the Solar Factor and the Solar Yield also for values.
For the HQ and LQ collector we observe that the behaviour of SY and SF increases with the increasing of the volume till the reaching of a plateau zone; in this zone it is not convenient anymore to enlarge the volume because the SF presents a very slight drop.
For the Vacuum tube the SY behaviour is similar to the previous cases; for the SF the maximum value is reached at 2326.5 lt.

The phenomenon of stagnation is strictly related to the storage tank volume: enlarging the volume of the tank, we increase the amount of water and energy stored in the tank. This means that for a high volume of stored water, the stratification in the tank is better defined because it is more difficult that the water is mixed up; in this way the energy is better conserved.

The following plots (Figure 12, Figure 13) represent the confrontation between SF and SY of the different collectors type.

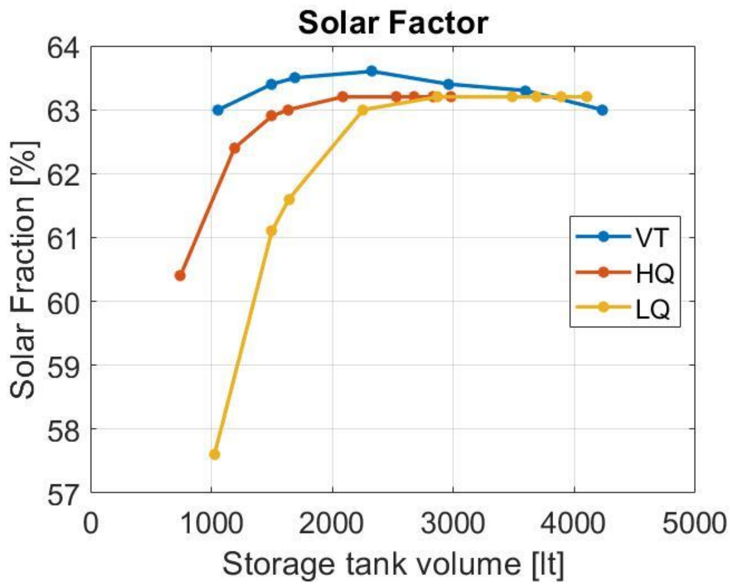

Figure 12 - SF with respect to storage tank volume

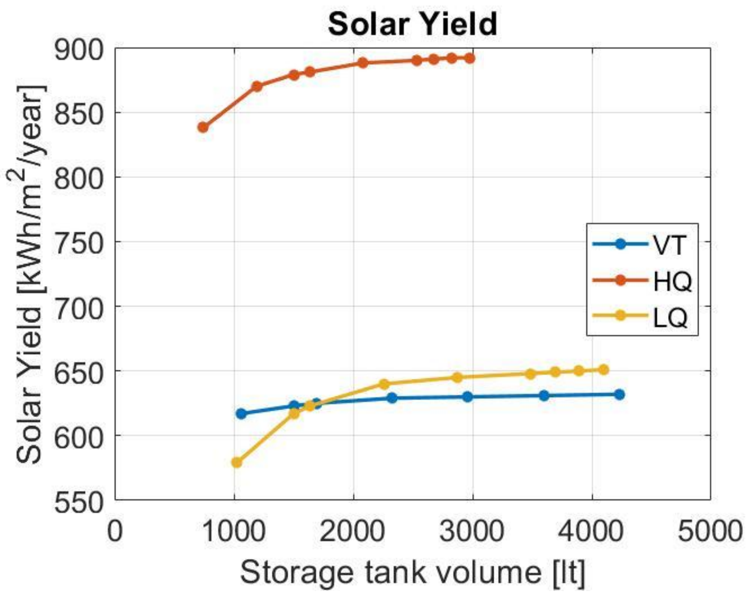

Figure 13 - SF with respect to storage tank volume

The table 3 resumes the final results obtained by the analysis. We observe that the plant with HQ collectors requires smaller tank volume, while the larger volume is required by Vacuum Tube system.

Table 3 - Optimal storage tank volume

	Optimal storage tank volume[lt]
High Quality	2083.2
Vacuum Tube	2326.5
Low Quality	2255

The optimal values that we obtain represent ideal tank volume for the parametric analysis. We are aware of the fact that real projects would need feasible and realistic tanks, produced in series. Surfing on the internet we investigated what could be a realistic size for a tank volume. From the website https://www.idrotop.com/riscaldamento/puffer-bollitori.html we expect different sizes for tank boilers. The most suitable would be the 2000 lt tank for the HQ and Vacuum Tube collector plant, while 2500 lt tank could be a good choice for the LQ collector plant: with lower volume we would decrease the Solar Factor, while for higher we would increase the costs.

The relationship between cost and volume tank is also interesting: the cost of the tank depends in general from materials or technology applied for the inner coil. The effective choice for the tank also depends on the structure of the building: the room where the tank will be installed can bring the decision for a boiler larger in height, or otherwise a larger base area with lower height value.

ADDITIONAL POINT

These are the graphs of the tank water temperatures at the top and bottom layers for the different collectors. (Figure 14, Figure 15, Figure 16) Comparing the various graphs we note that they have a similar trend.

The hottest layer for the HQ collector remains around 55 ° C with peaks of a few degrees during the hottest hours of the day and a slight increase in the summer. The temperature of the LQ collector has a similar trend to the HQ only that in summer it reaches 60 ° C. Finally, by comparing the temperature of the top layer for the VT collector, it is observed that it has the same trend as the HQ collector.

The temperatures remain constant because our tank volume is large enough, there is a lot of water and a lot of energy and therefore the temperature remains uniform during the year, there are just few variations.

The temperature of the top layer in winter remains constant at 55 ° C. The temperature of the lowest state of the tank, arriving from the panels, in winter is lower than in the summer. This is because the irradiation in winter is lower than in summer and the water in the lower layer has not yet mixed with the rest of the water in the tank.

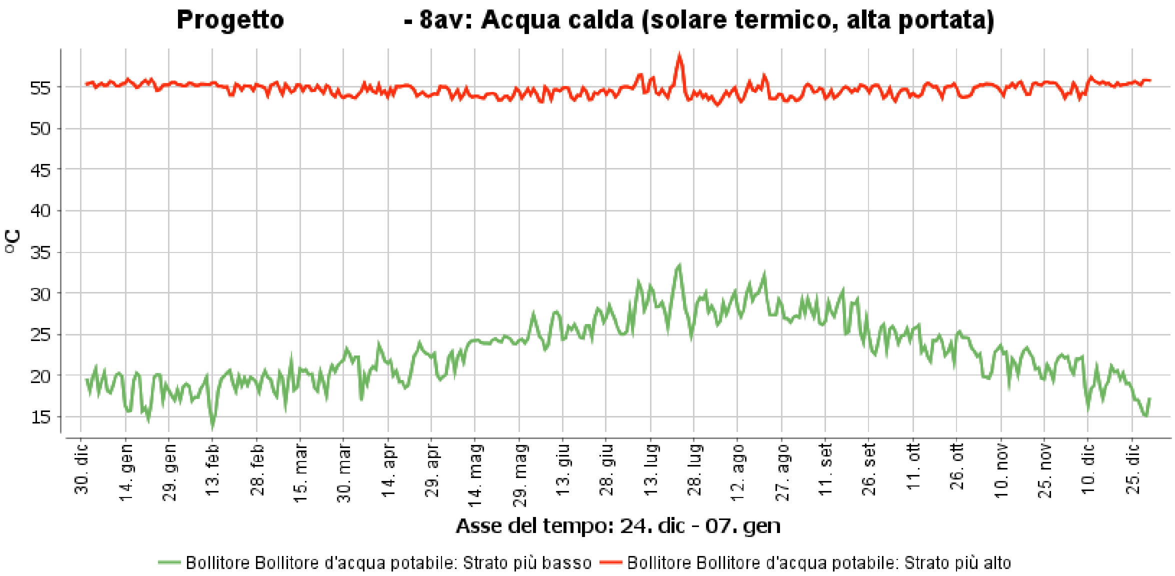

Figure 14 - Boiler stratification HQ

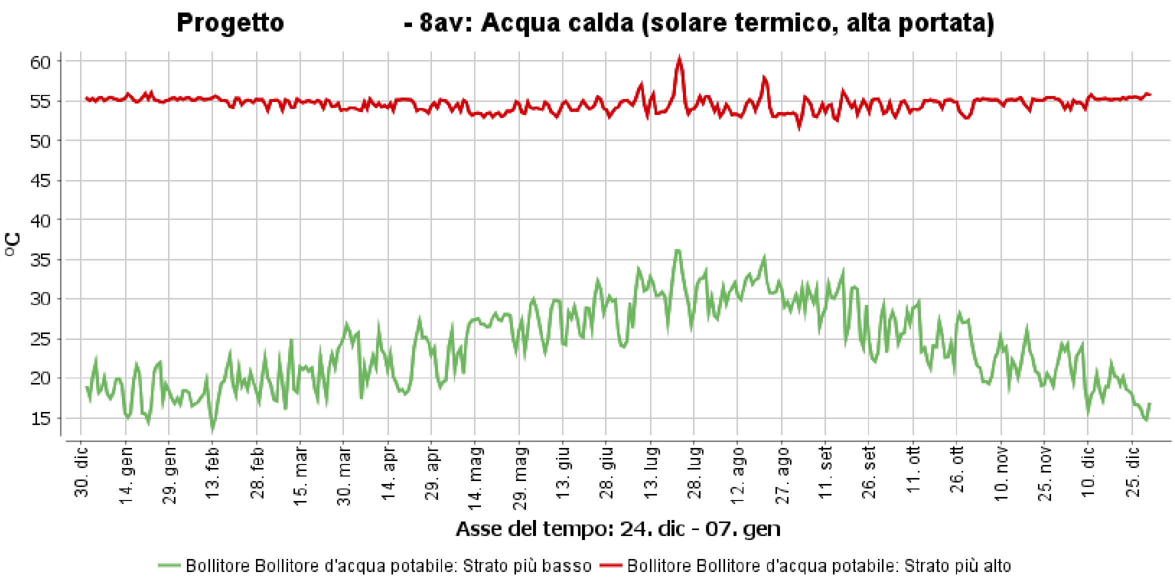

Figure 15 - Boiler stratification LQ

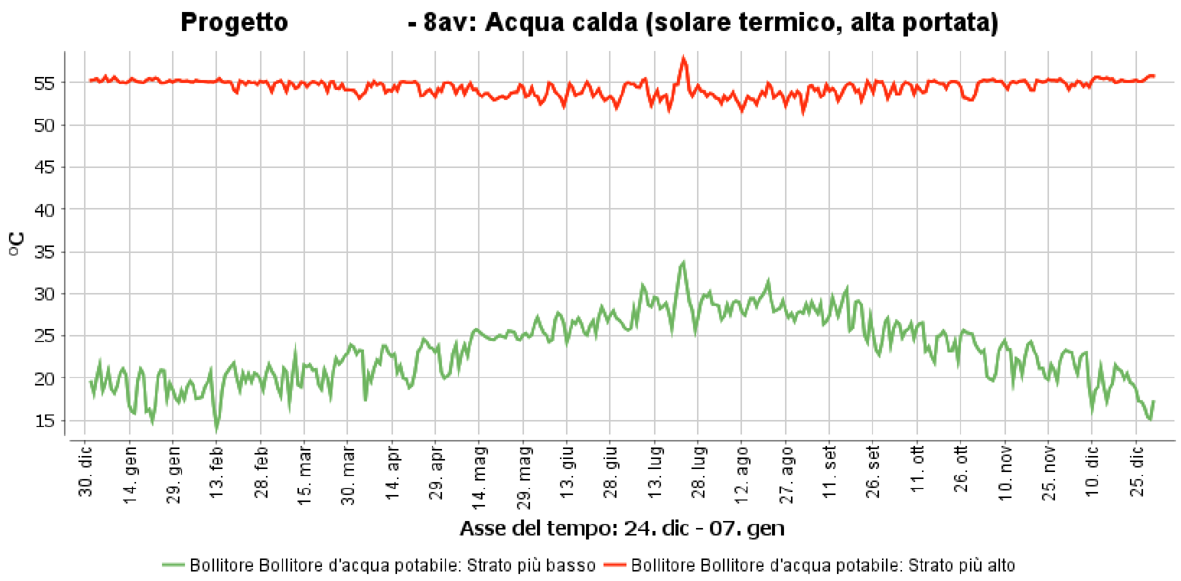

Figure 16 - Boiler stratification VT

Below we have the graphs of solar collectors' outlet temperature (Figure 17, Figure 18, Figure 19). The trend of HQ, LQ and VT collectors is almost the same, in winter temperatures fluctuate daily between 10 and 30 °C. In summer, the temperature exceeds 30 °C and in July the temperature reaches 45 °C. The outlet temperatures do not depend on storage.

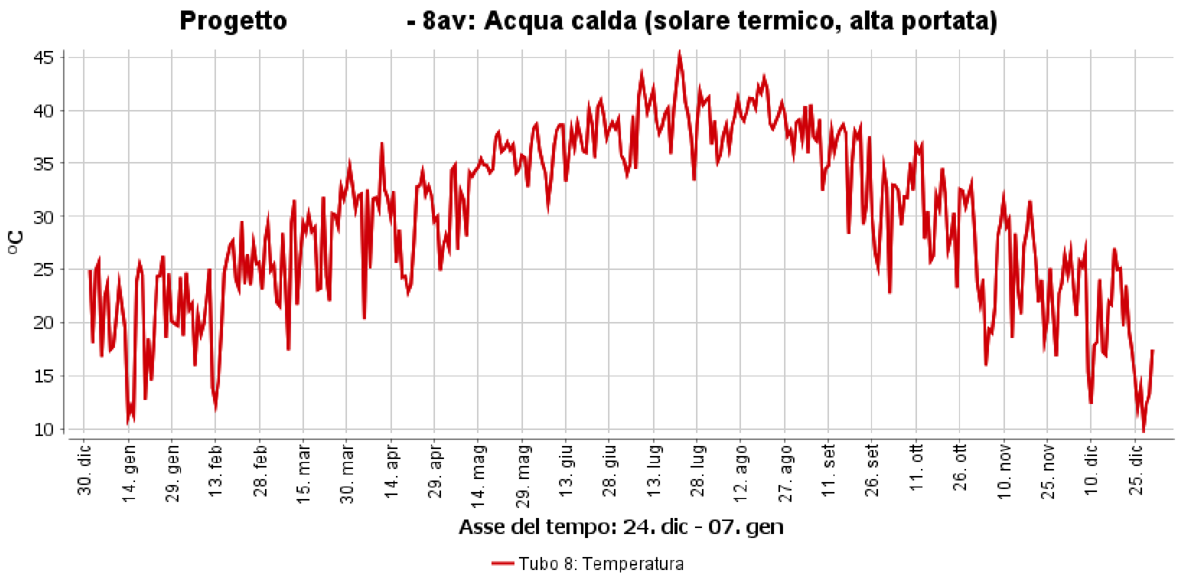

Figure 17 - Collectors outlet temperature HQ

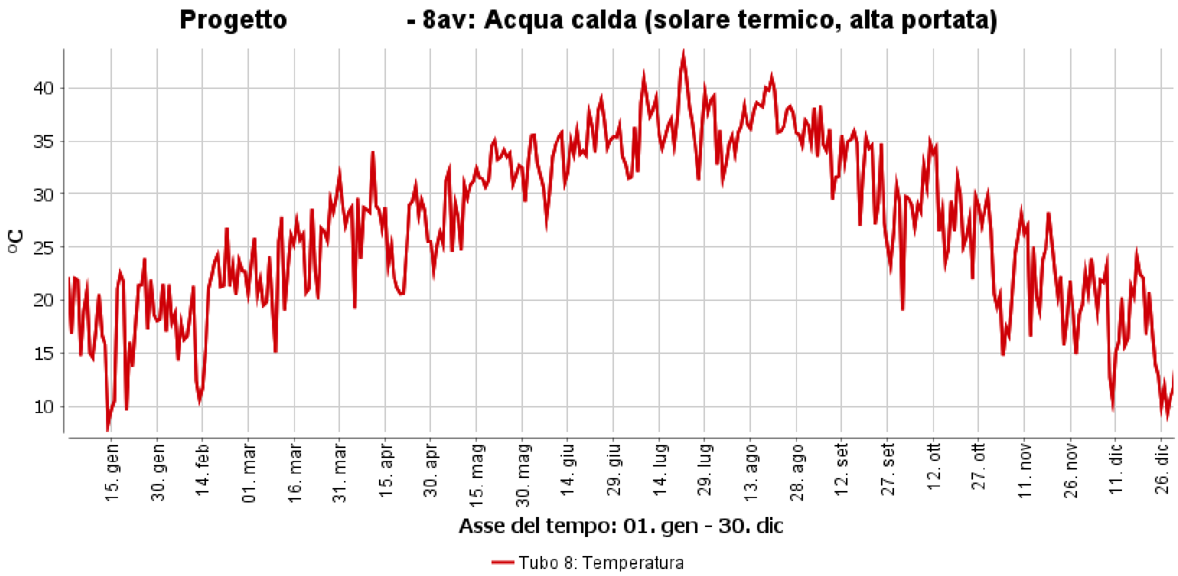

Figure 18 - Collectors outlet temperature LQ

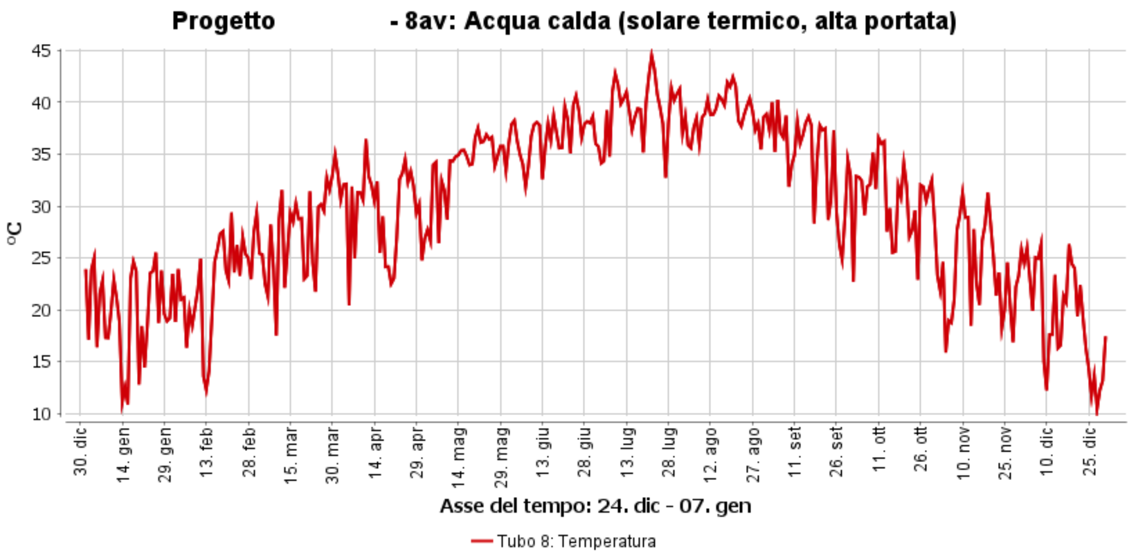

Figure 19 - Collectors outlet temperature VT

Here are the graphs of internal heater power for the different collectors for the optimal values (Figure 20, Figure 21, Figure 22). We can notice that the values for the Low Quality collector are higher than the other two, because we need more auxiliary power (Qaux), instead High Quality collector and Vacuum tube need less auxiliary power because they produce more power from the panels.

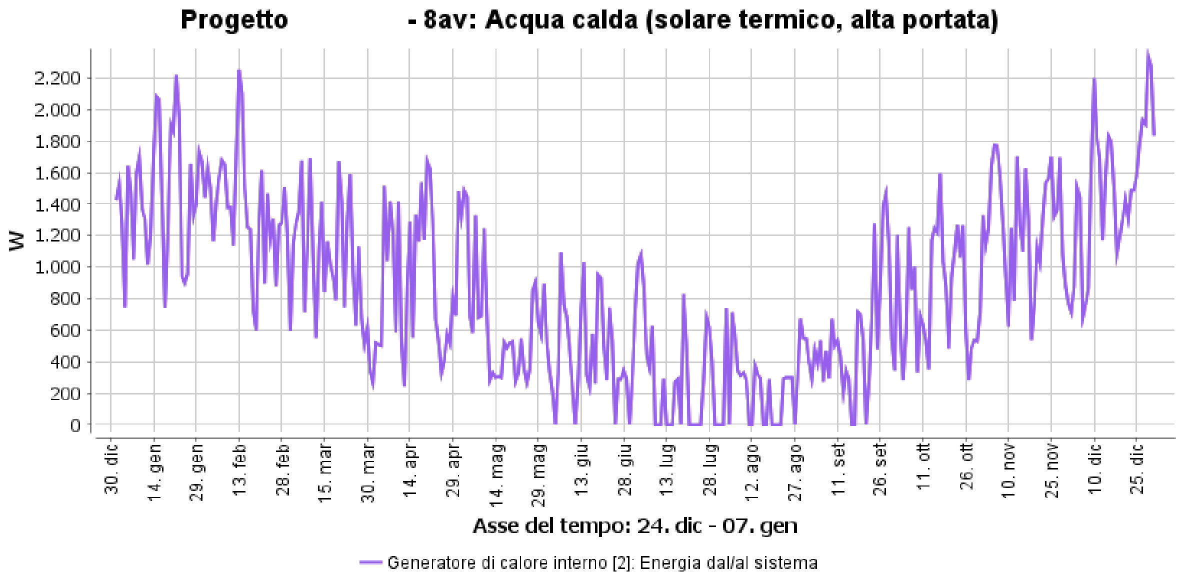

Figure 20 - Qsol for HQ

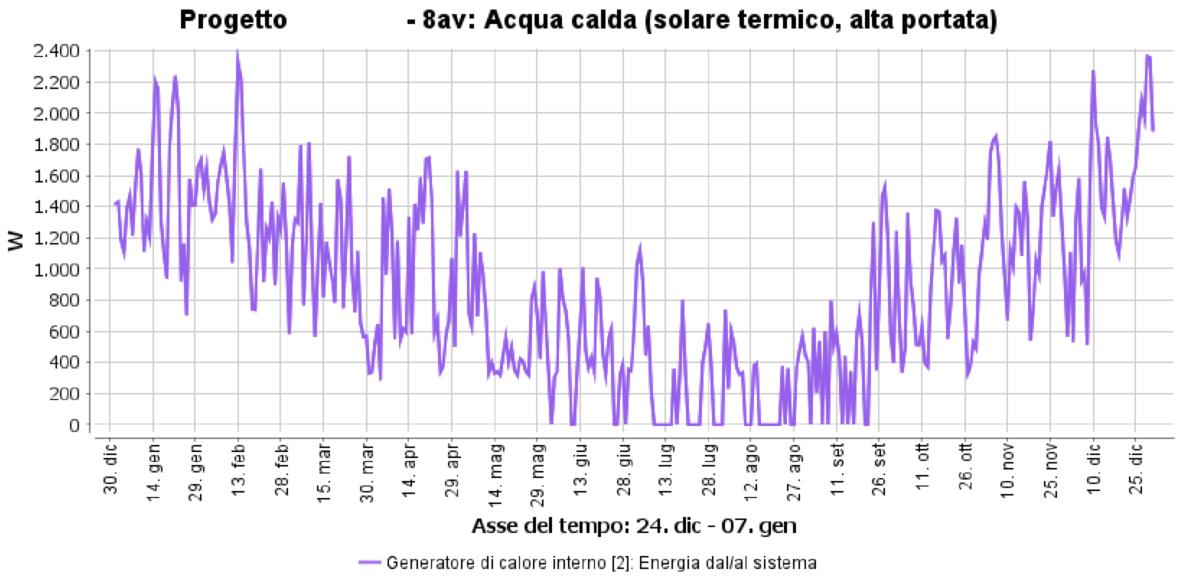

Figure 21 - Qsol for LQ

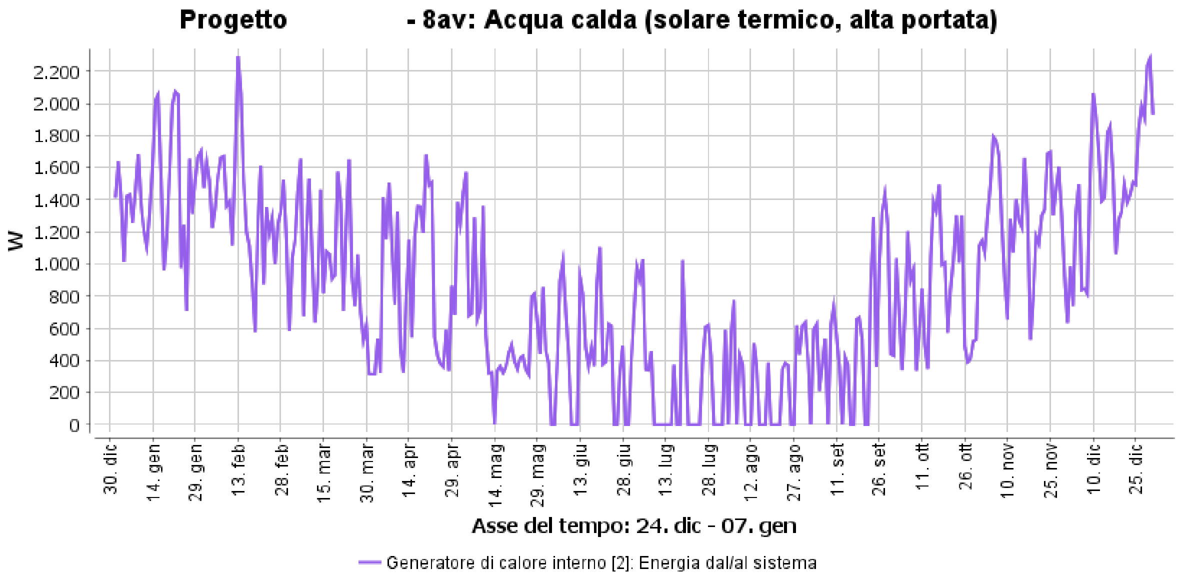

Figure 22 - Qsol for VT

Qaux initially decreases and then starts to rise again, the winter months are those with the highest Qaux.
Qaux has an opposite trend with respect to the temperature leaving the collectors. When the temperature is high it means that the collectors are providing enough energy to water in the solar loop; when the temperature is low, we have to use the auxiliary power.

STEP 5

To optimize our system we decided to perform two different variations of the original plant and see which improvement helps us the most.

- Two Tanks

This improvement consists in utilizing two tanks, one for pre-heating and one connected to the auxiliary, instead of only one tank. The first tank is directly connected to the solar loop, while the second one is filled by the first one, in particular by water in its top layer, this second tank is the one that provides hot water to the user.

We decided to keep the total volume of the boilers constant and equal to the optimal value found in step 4, therefore for the two tanks configuration each boiler has a volume of half of the optimum.

The obtained scheme is in figure 23:

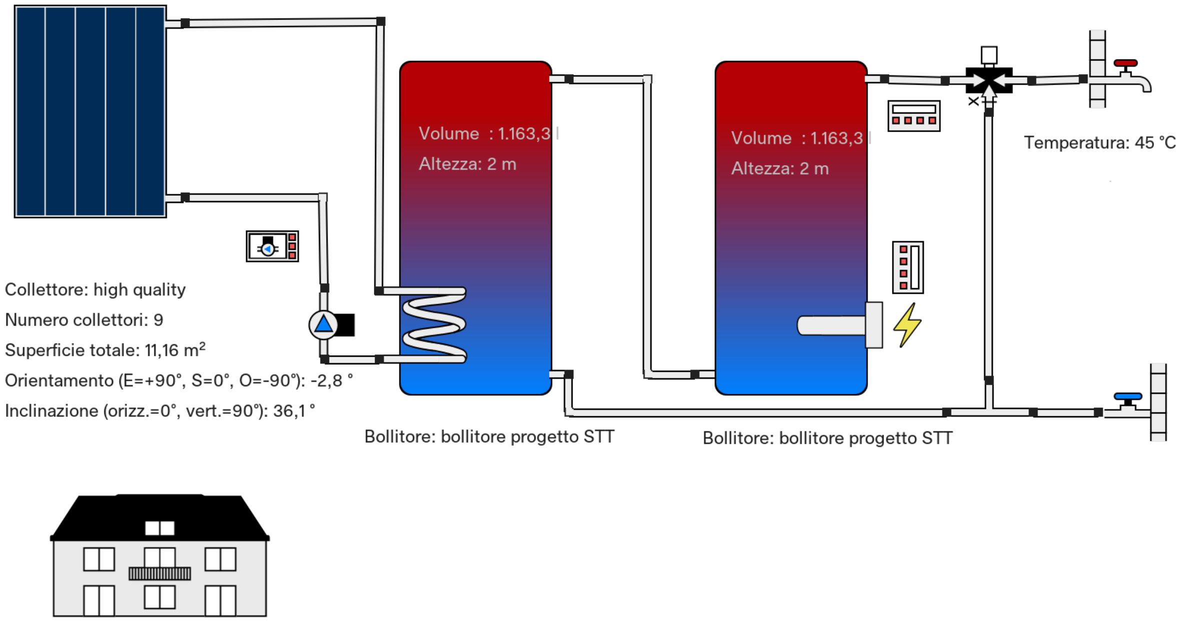

Figure 23 - Two tanks configuration

Comparing this configuration with the previous one we obtain (Table 4, 5, 6 and Figure 24, 24, 26):

1. For HQ Collector

Table 4 - Comparison between the two configurations

Confronto varianti:		1 Tank	2 Tanks
SF	%	63.2	64.8
Qsol	kWh	13 208	13 623
Qaux	kWh	7 685	7 413

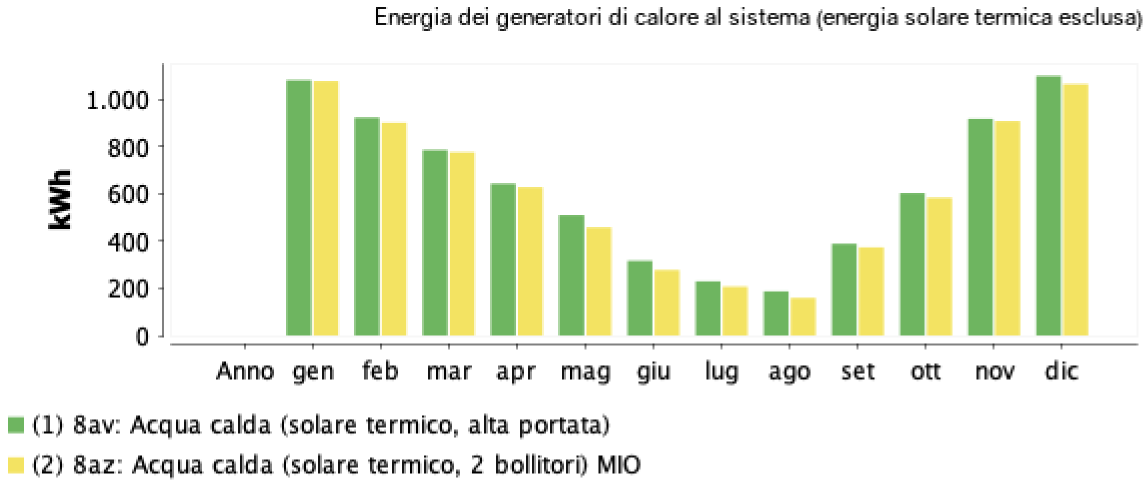

Figure 24 - Qsol for the two configurations

2. For LQ Collector

Table 5 - Comparison between the two configurations

Confronto varianti:		1 Tank	2 Tanks
SF	%	58.7	66.1
Qsol	kWh	12 100	13 878
Qaux	kWh	8 514	7 131

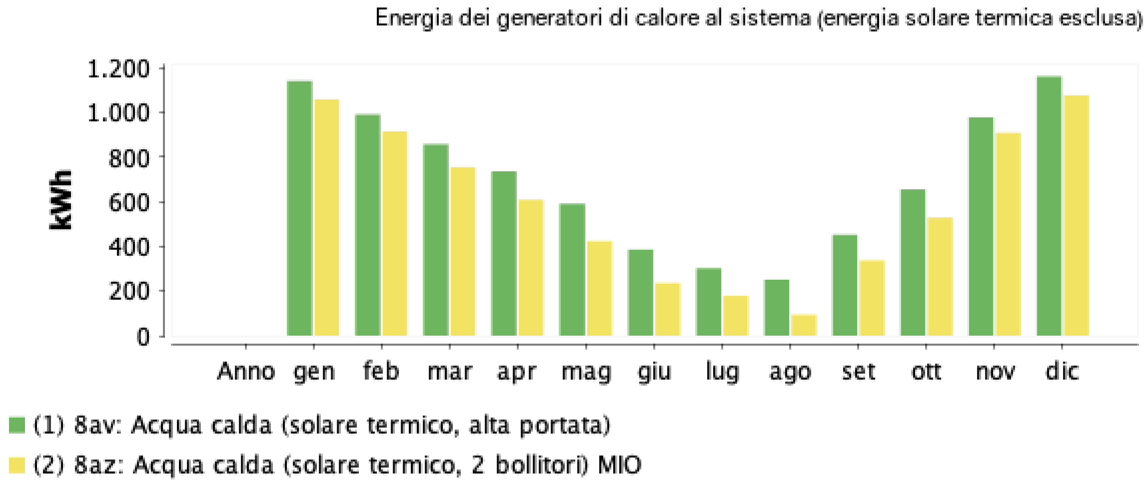

Figure 25 - Qsol for the two configurations

3. For VT Collector

Table 6 - Comparison between the two configurations

Confronto varianti:		1 Tank	2 Tanks
SF	%	63.2	64.6
Qsol	kWh	13 102	13 630
Qaux	kWh	7 636	7 461

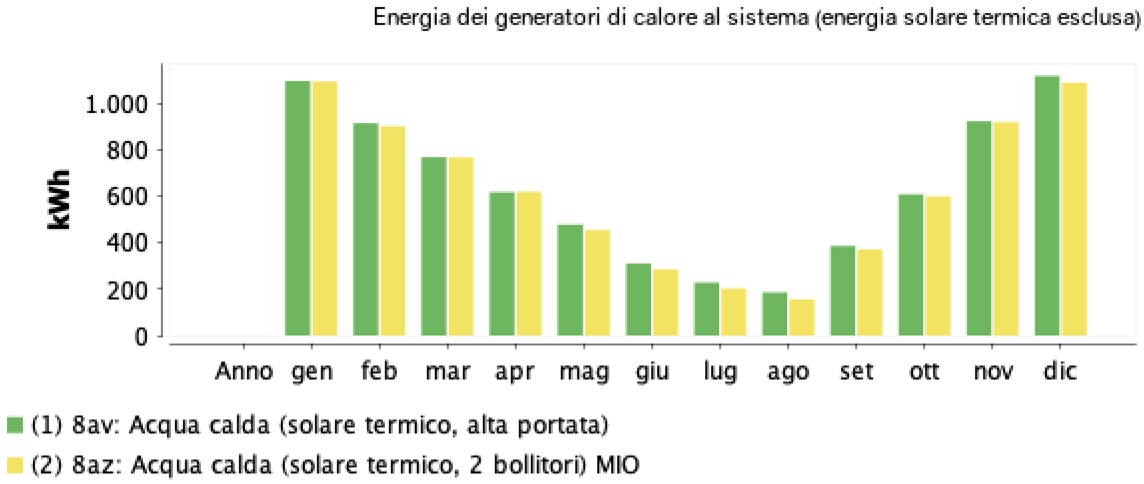

Figure 26 - Qsol for the two configurations

From the obtained results we can see that the Solar Factor increases along with Qsol in the second configuration, while Qaux decreases. This is because with two smaller tanks we are able to keep the water warmer, therefore we are using more hot water coming from the collectors and less auxiliary.
In fact the most important feature of our tank is that it has to be an heat storage instead of a mass storage, so even if there is less water in each tank, since this water is warmer, for us is a gain.

Another important feature of this new configuration is that the cold water coming from the aqueduct goes just in the pre-heating tank, it warms up and then moves to the second tank in which there are no cold water sources but just the auxiliary who works only when needed. Overall we can notice a better exploitation of the heat coming from the solar collectors.

We can also say that this improvement works better with the low quality collector, while for high quality and vacuum tube collectors what we gain is so little that it might not be a good idea to invest more money in this complex configuration. However if we choose to spend less on the collectors, buying LQ ones, we can then decide to invest in this improvement that makes the plant work with similar features with respect to HQ and VT systems.

If we imagine to apply this improvement on a real plant, we have to consider a few issues that can concern the case. Firstly we must consider the real room in the building dedicated to the tanks: depending on the space we can choose different tanks with the same volume but different shapes (larger in height or base area). The maintenance costs are another factor that we have to take into account for the evaluation of the NPV: two tanks increase the maintenance costs and this will consequently increase the Pay Back time of the plant.

- Different Flow Rates

Keeping the same initial configuration with just one boiler, we have also tried to change the water flow rate of the circuit, in particular for the high quality solar collector we used: (1) 40 l/h/m^2, (2) 60 l/h/m^2, (3) 80 l/h/m^2, (4) 100 l/h/m^2.

In trying this improvement we wanted to see if with higher flow rates we obtained higher values of SF and in general better performances for the system. For simplicity we have done this improvement just for the high quality collector. We obtained (Table 7, Figures 27, 28):

Table 7 - Comparison between the four configurations

Confronto varianti:			40 l/h/m^2	60 l/h/m^2	80 l/h/m^2	100 l/h/m^2
Frazione solare: percentuale di energia solare al sistema	SFn	%	63,2	65	65,3	65,3
Energia solare termica al sistema	Qsol	kWh	13.208	13.557	13.625	13.632
Energia dei generatori di calore al sistema (energia solare termica esclusa)	Qaux	kWh	7.685	7.316	7.227	7.229
Consumo d'energia totale	Quse	kWh	19.466	19.466	19.467	19.466
Deficit d'energia	Qdef	kWh	49	49,2	49,6	49,2
Consumo totale di energia elettrica e/o combustibile del sistema	Etot	kWh	8.107	7.717	7.620	7.624
Consumo elettrico totale	Ecs	kWh	8.107	7.717	7.620	7.624
Fattore di energia primaria	eP		0,75	0,71	0,7	0,7

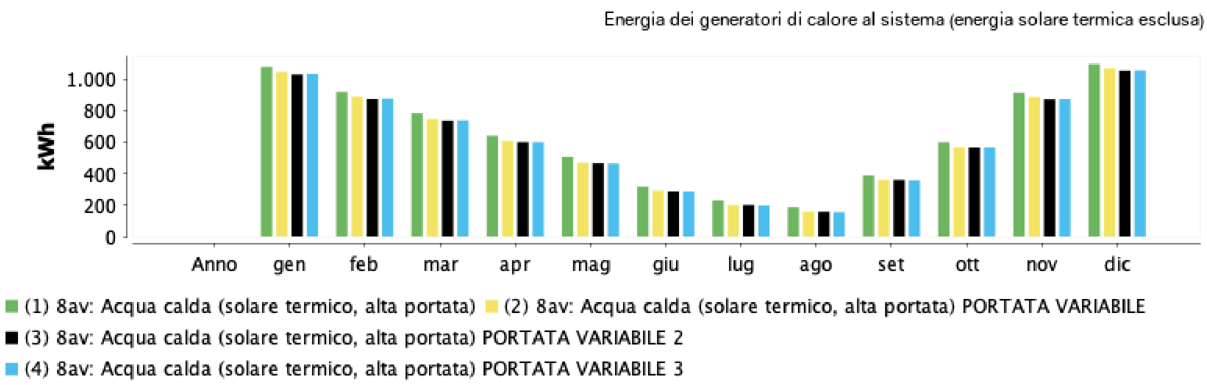

Figure 27 - Qaux for the four configurations

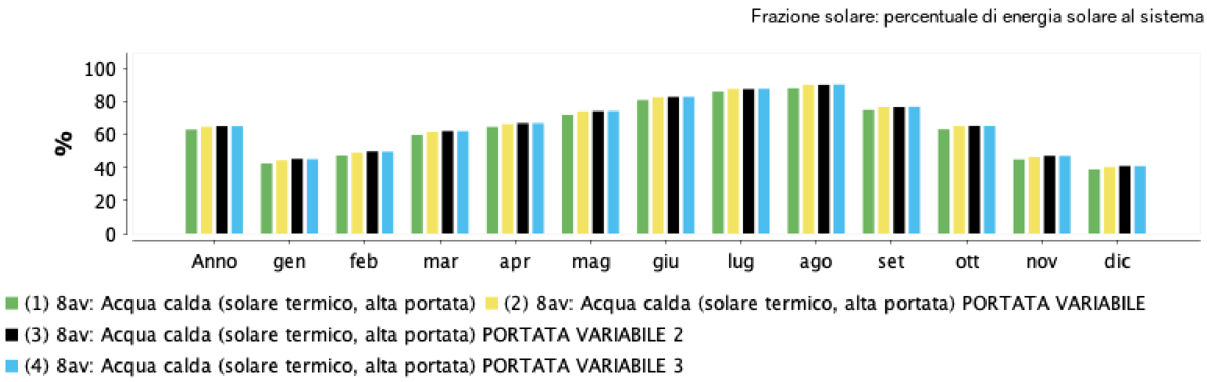

Figure 28 - SF for the four configurations

Switching the flow rate from 40 l/h/m^2 to 60 l/h/m^2 we can increase our SF of almost two percentage points, consequently the Qaux slightly decreases. We can also see that further increasing the flow rate does not benefit us: from 60 l/h/m^2 to 80 l/h/m^2 the SF goes from 65% to just 65.3% and from 80 l/h/min to 100 l/h/min it remains unchanged.
So at around m=60 l/h/m^2 we reach a plateau and our SF does not increase anymore, therefore it is useless to spend more money for an higher mass flow rate.

Increasing too much the mass flow rate can also lead to high pressures in the pipelines which are a vital component of the system. When the pressure is too high it has to be released somewhere so the pipelines may spill liquid in their most fragile points and then we would have to refill water.

PART 2

ECONOMIC ANALYSIS

The economical part is carried out evaluating the NPV for each type of panel and calculating the Payback Time for the optimal configuration.

The table 8 reports the assigned data for the economic analysis; our system concerns auxiliary fed by electricity.

Table 8 - Data for economic analysis

interest rate	2	%
energy cost	0.10	€/kWh
energy increase rate	4	%
life time of installation	20	years

In Italy the cost of energy is around 0.18-0.22 €/kWh for private users: 0.10 €/kWh the cost of the heat supply gained by natural gas, even if in our project we consider an electrical supply.

For a more accurate analysis we can consider the weighted average cost of capital (WACC): the interest rate fixed at 2% is however a good method for economic evaluation. The variation of this parameter consists of sensitive analysis.
The Effective interest rate is evaluating starting from the interest rate and the energy cost:

$$i' = \frac{i-e}{1+e}$$

The investment costs I include the collectors, the piping, control and electrical supply, pump, storage and insulation. This approximation works with this project: not all these costs increase linearly with the surface. The scope of the project is to study the variation of the total cost and not proper the figure of the investment. The investment cost reported in the table 9 is referred to the gross area:

Table 9 - Investment cost

FPLQ solar collectors	500	€/m^2
FPHQ solar collectors	750	€/m^2
VT solar collectors	700	€/m^2

For the technical data it is required to satisfy the following ratios (Table 10):

Table 10 - Ratios for technical data

Vtank/Ac	75	lit/m^2
Shex/Ac	0.1-0.2	m^2/m^2

The analysis must be performed considering the optimal values of orientation and tilt angles of part 1. For each type of solar collector we evaluate the optimal areas, maximizing the NPV. For the last step calculate the Pay Back time, as the number of years wherefore the NPV is equal to 0.
Once we set the optimal values in the POLYSUN software, we evaluate the NPV.
The Net Present Value takes into account the time value of money: considering our three solar collectors projects we can evaluate and compare the capital:

$$NPV = - I + \frac{S_{savings}}{(1+i)^n} - M_{ordinary}$$

The maintenances are considered with the following formula:

$M_{ordinary} = 0.01 * E_{prod}$ considered every year
$M_{extraordinary} = 0.15 * I_{cost}$ considered in year 11

For the savings we take into account the solar factor and the auxiliary power:

$$Q_{aux\,0} = \frac{Q_{aux}}{(1-SF)}$$
$$\Delta Q_{aux} = SF * Q_{aux\,0}$$
$$R_{energy} = \Delta Q_{aux} * c_{energy}$$
$$S_{savings} = R_{energy} * (1 + e)$$

The formula of the NPV is confronted with the comulated:

$$C = I + S_{savings} - M_{ordinary}$$

Concerning the ratio Vtank/Ac we are not able to respect it: the optimal tank volumes that we found with the previous steps are higher than the averages. This fact is not negligible because it can bring problems of costs, space and available models for the dimensions. However, the high capacity of the tanks avoids issues like the stagnation fenomenon: the flow rate never assumes a value of zero, so temperatures higher than 60 °C are never reached.
In general we expect for Barcelona higher value of NPT considering Turin.

Vacuum Tube solar collector
The optimal values are the following. (Table 11)

Table 11 - Recap of optimal values for VT

beta	36.1	°
gamma	-2.8	°
Volume	2326.5	lt

In the table 12 are reported the values of NPV related to the values of area.

Table 12 - NPV with respect to collector area

collettori	**gross area**	**coil surface**	**V/Ac**	**Qsol**	**Qaux**	**SF**	**SY**	**NPV**
	m2	m2	lt/m2	kWh	kWh	%	kWh/ m2	€
14	32.91	3.62	70.7	18159	3363	84.4	552	13048.29
13	30.56	3.36	76.1	17473	3904	81.7	572	13261.19
12	28.21	3.10	82.5	16681	4541	78.6	591	13530.05
11	25.86	2.84	90.0	15739	5335	74.7	609	13411.38
10	23.51	2.59	99.0	14573	6407	69.5	620	12801.90
9	21.16	2.33	109.9	13263	7661	63.4	627	11802.51

The figure 29 represents the NPV as a function of the collector area.

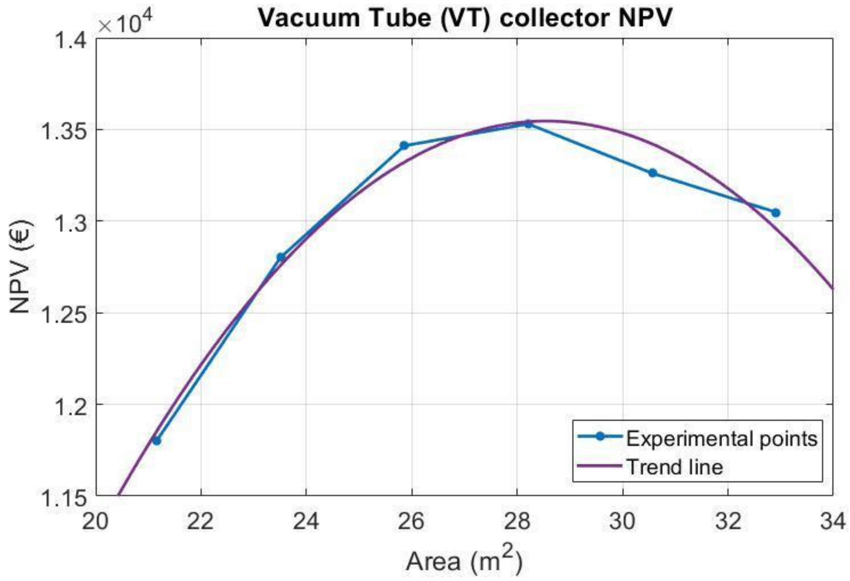

Figure 29 - NPV with respect to collector area

As we can see the NPV optimal value is found at area 28.21 m^2 for 12 collectors. The figure 30 shows the NPV behaviour compared with the cumulated through the 20 years.

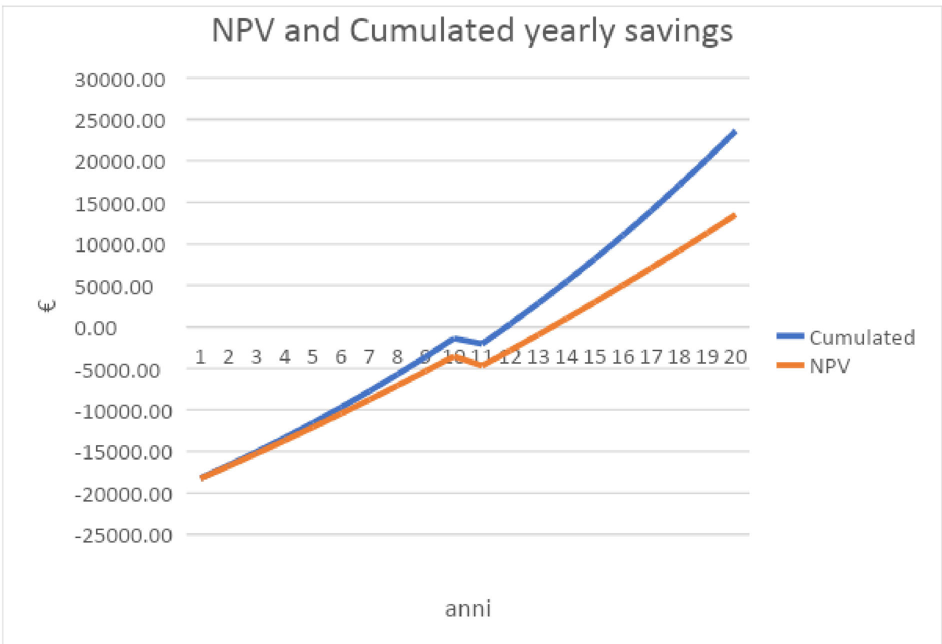

Figure 30 - NPV for VT

The Pay Back Time is 13 years.

FP High Quality solar collectors

The optimal values are the following. (Table 13)

Table 13 - Recap of optimal values for HQ

beta	37.2	°
gamma	-5	°
Volume	2083.2	lt

The table 14 represents the NPV as a function of the collector area.

Table 14 - NPV with respect to collector area

collettori	**gross area**	**coil surface**	**V/Ac**	**Qsol**	**Qaux**	**SF**	**SY**	**NPV**
	m2	m2	lt/m2	kWh	kWh	%	kWh/m 2	€
19	23.56	2.59	88.42	18033	3361	84.3	765	17941.82
18	22.32	2.46	93.33	17570	3724	82.5	787	18892.15
17	21.08	2.32	98.82	17074	4143	80.5	810	18986.33
16	19.84	2.18	105.00	16521	4616	78.2	833	18873.62
15	18.6	2.05	112.00	15861	5198	75.3	853	18386.20
14	17.36	1.91	120.00	15077	5913	71.8	868	17734.54

The figure 31 represents the NPV as a function of the collector area.

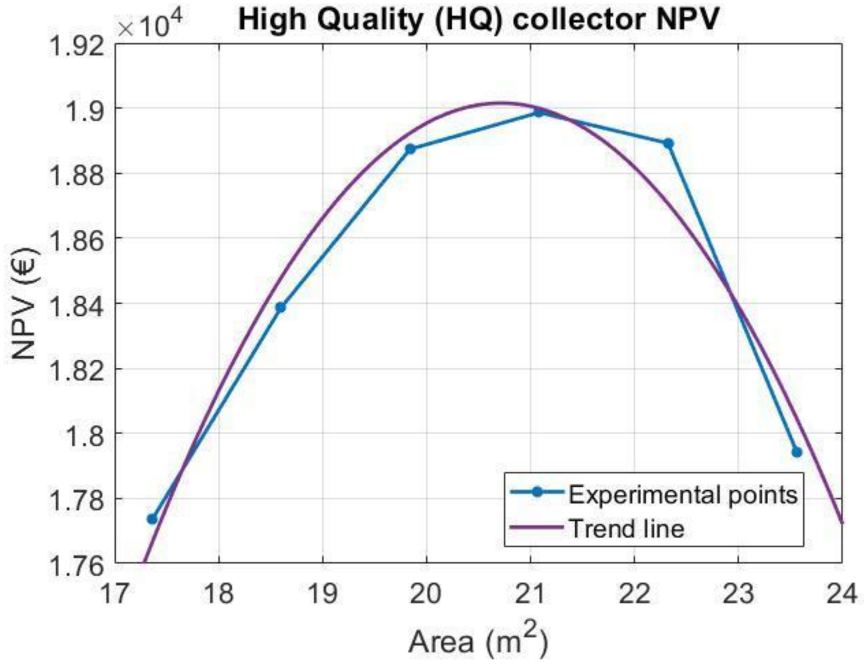

Figure 31 - NPV with respect to collector area

As we can see the NPV maximum value is found at area 21.08 m^2 for 17 collectors.

The figure 32 shows the NPV behaviour compared with the cumulated through the 20 years.

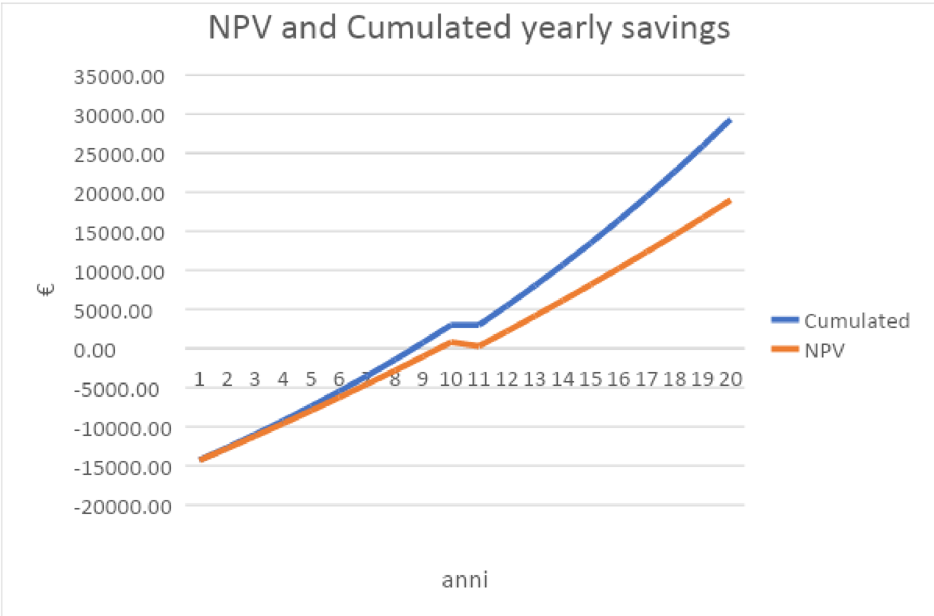

Figure 32 - NPV for HQ

The Pay Back Time is 10 years.

FP Low Quality solar collector

The optimal values are the following. (Table 15)

Table 15 - Recap of optimal values for LQ

beta	38.6	°
gamma	-8.6	°
Volume	2255	lt

The table 16 represents the NPV as a function of the collector area.

Table 16 - NPV with respect to collector area

collettori	**gross area**	**coil surface**	**V/Ac**	**Qsol**	**Qaux**	**SF**	**SY**	**NPV**
	m2	m2	lt/m2	kWh	kWh	%	kWh/m2	€
20	41	4.51	55.00	17577	3575	83.1	429	14620.96
17	34.85	3.83	64.71	16869	4217	80	484	16612.10
15	30.75	3.38	73.33	16239	4781	77.3	528	17701.98
12	24.6	2.71	91.67	14685	6230	70.2	597	17741.53
10	20.5	2.26	110.00	13118	7716	63	640	16763.08
7	14.35	1.58	157.14	9673	11076	46.6	674	12748.77

The figure 33 represents the NPV as a function of the collector area.

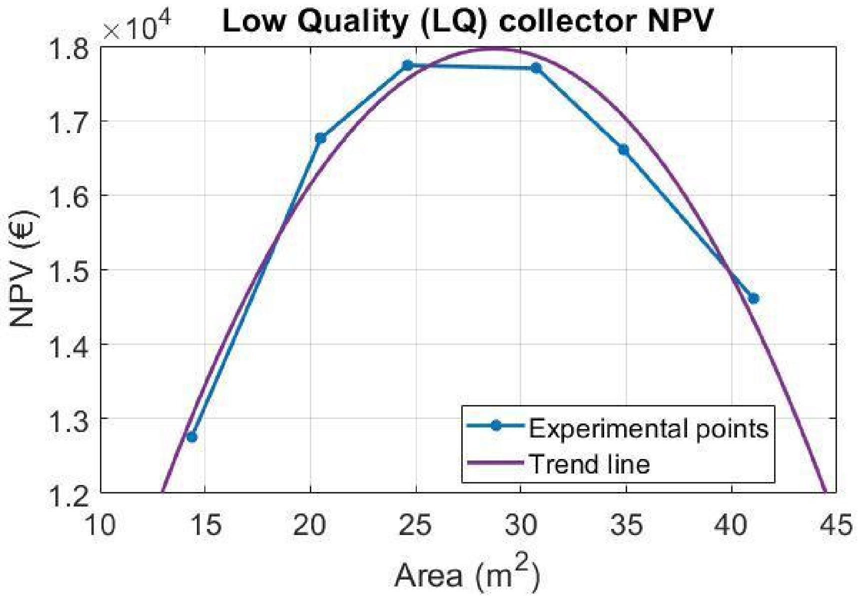

Figure 33 - NPV with respect to collector area

As we can see the NPV maximised value is found at area 24.6 m^2 for 12 collectors.
The figure 34 shows the NPV behaviour compared with the cumulated through the 20 years

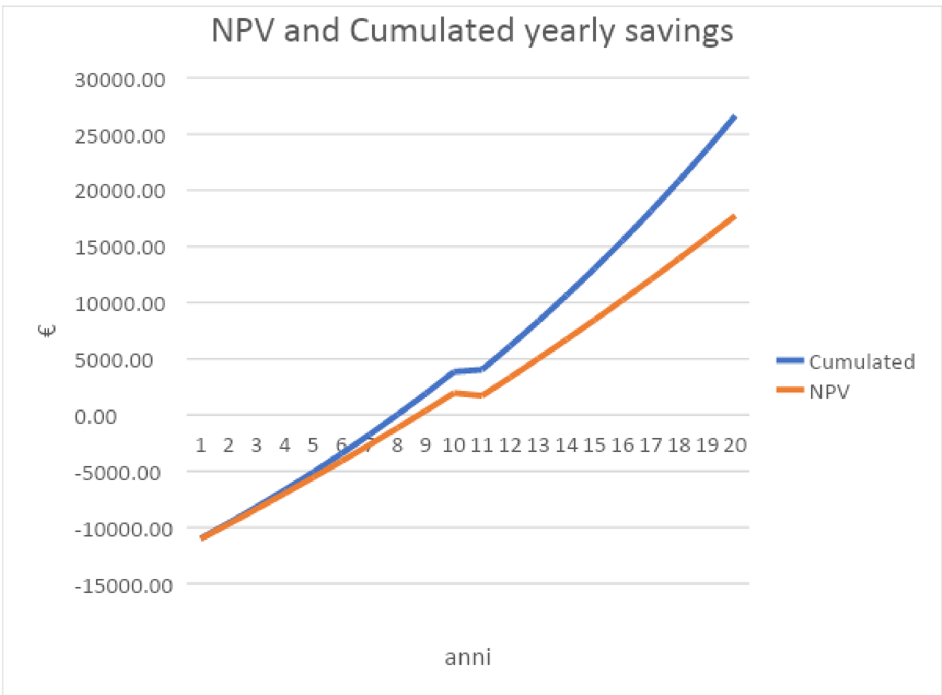

Figure 34 - NPV for LQ

The Pay Back Time is 9 years.

The conceptual difference between NPV and Cumulated is in taking into account the economical value of the money for plants like ours: the NPV considers the interest rate in the formula. If we enlarge the interest rate, we will experience a variation in the linearity of the NPV during the years: the value of the money decreases, with consequent increasing of Pay Back time. If we decrease the interest rate, the value of the money drops, reducing the Pay Back time

If we just consider increasing energy inflation rate, the investment will provide better return on an almost linear cumulative function.

If we take into account the combined effect of energy inflation rate and interest rate, higher interest rate will command over energy inflation rate. For a low interest rate we have the opposite condition.

The following plot shows the case for vacuum tube: (Figure 35)

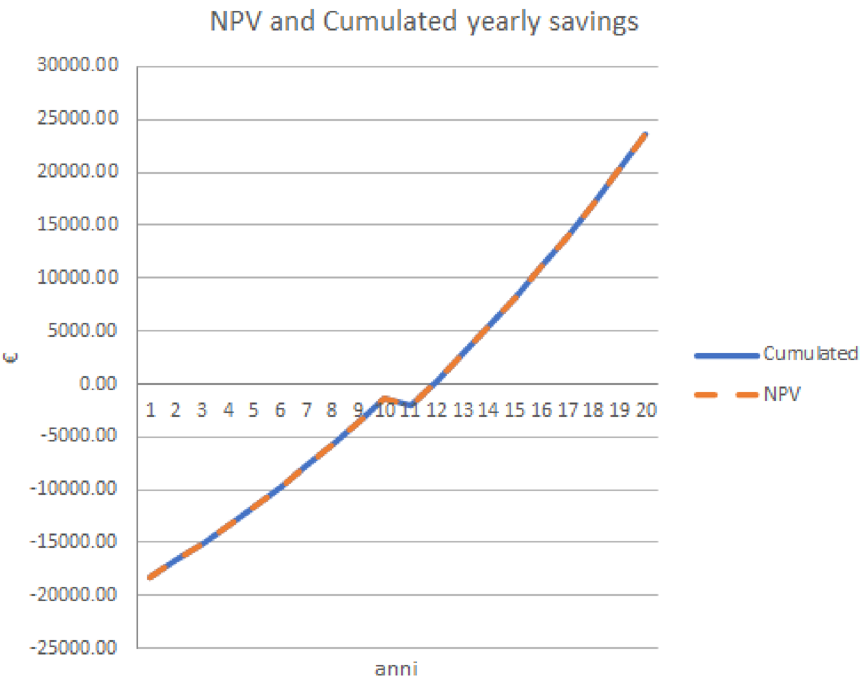

Figure 35 - Case without inflation for VT

The data set is shown in the table 17:

Table 17 - Interest rate and energy increase rate

interest rate	0	%
energy increase rate	4	%

This is the case for Vacuum Tube solar collectors where the cumulated is coincident to the NPV: the cumulated doesn’t consider the interest rate, so the analysis considers the same behaviour during the time.

Energy market is growing, so the increase rate in the cost of energy is quite high, equal to 4% every year.

If we consider a dystopian scenario with high level of inflation and the energy market is flourishing, our NPV will present a different behaviour as shown in the picture 36:

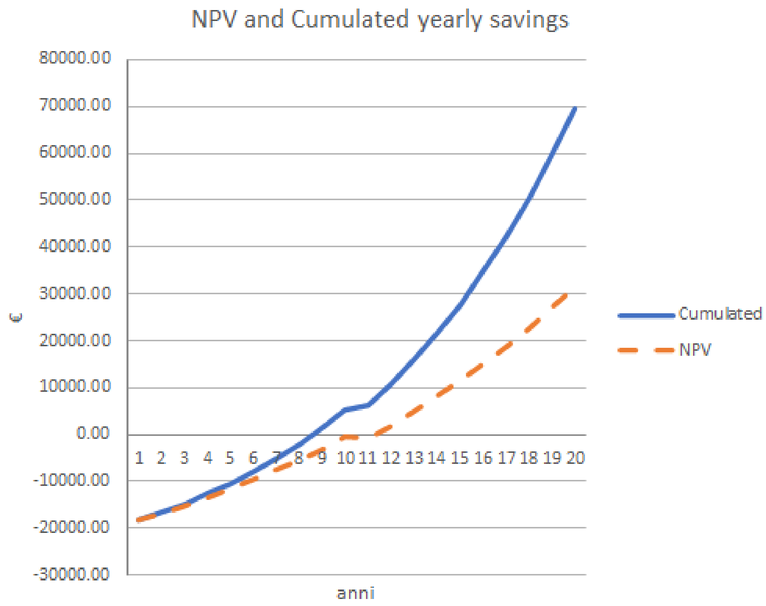

Figure 36 - Growth in the energy sector scenario

The data considered are written in the Table 18:

Table 18 - Interest rate and energy increase rate

interest rate	4	%
energy increase rate	10	%

The cumulated quantity is not dependent on interest rate, so the great values that we obtain are given by high level of energy cost. The NPV proves the dependence of the interest rate at 4%, showing lower values with respect to the cumulated.

The economical analysis is also performed for the worst case scenarios, considering high crise in the energy sector. For this analysis we consider the energy increase rate with zero value reported in Table 19: this means that the energy market is not growing. It's not convenient to install this kind of plant.

Table 19 - Interest rate and energy increase rate

interest rate	0	%
energy increase rate	0	%

The figure 37 shows that the Pay Back time is about 15 years, if the cost of energy is null:

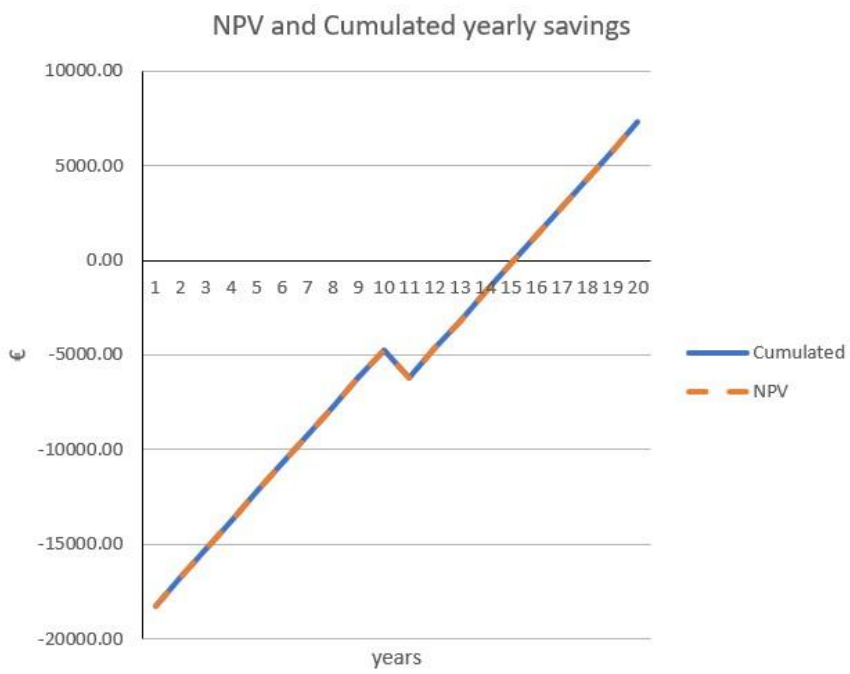

Figure 37 - Zero cost of energy scenario

The last scenario considers a negative energy increase rate, showing the worst case scenario. Data are reported in Table 20.

Table 20 - Interest rate and energy increase rate

interest rate	0	%
energy increase rate	-5	%

The figure 38 shows that it is not convenient to build this plant under these conditions. The Pay Back time is never reached.

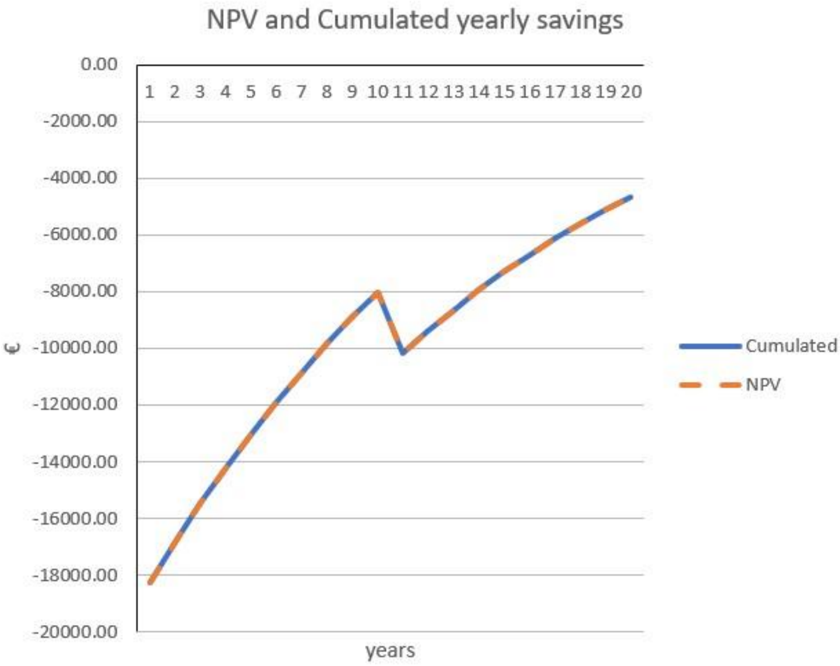

Figure 38 - Huge crisis in the energy market scenario

PART 3

POINT A

In order to increase the living standards in both commercial and residential buildings, summer cooling and air conditioning represent a growing market all around the world.
This technology can be combined with solar heating and domestic hot water: these features contribute to more environmentally friendly buildings.

Moreover, the cooling demand peak corresponds to the availability peak of the solar radiation: another point in favour of this technology.
Our building under study is located in Barcelona: we expect this application as a great solution to face up to the summer heat of Catalonia.

In order to study the solar cooling technology applied to our project, we consider a new plan 71a on software Polysun.

The scheme is shown in the figure 39 below.

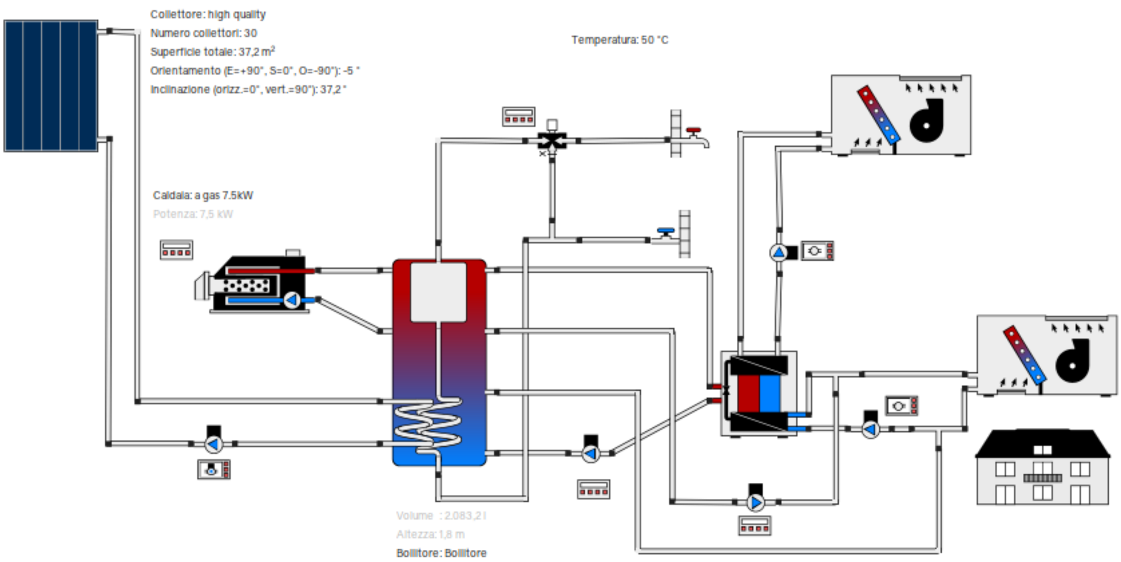

Figure 39 - Solar cooling layout

In the circuit we consider the chiller AC708, characterized to be an adsorption chiller model. The schematic represents the cooling tower as fan coils exchanging heat with the outside.

In order to satisfy the cooling demand, we start matching different combinations of plant sets.Starting from the chiller, we can increase the size of the chiller or edit its performance. We can also increase the size of the storage volume, modifying the setpoint temperature. Moreover we can increase the number of fan coils or adjust the available solar or auxiliary driving power.
Different performances are obtained by changing the type of loop to ground loop or water loop.

We decide to proceed setting the High Quality solar collectors with the optimal storage tank and optimal angles found for our location. We decide to leave 18 °C for the setpoint temperature while we drastically decrease the hot water demand from 200 to 10 lt/day. Because this first combination wasn't satisfying the cooling demand, we increase the water demand up to 50 lt/day.
The operating conditions are shown in table 21.

Table 21: Operating conditions point 3

cooling tower [fan coils]	20
internal fan coils	12
hot water demand [lt/day]	50
setpoint temperature [°C]	18
output requested temperature [°C]	50
people for the supply	4

Once we find the right configuration to satisfy the demand, we perform a parametric analysis for the three solar collector types. The scope is to compare the different Solar Factor for the models in order to investigate the different behaviors.
We are interested in the three summer months of June, July and August: we will consider the integral average of the monthly Solar Factor for those specific periods.
The analysis is performed by varying the number of collectors and registering the monthly SF. We expect that increasing the area, also the solar factor will increase

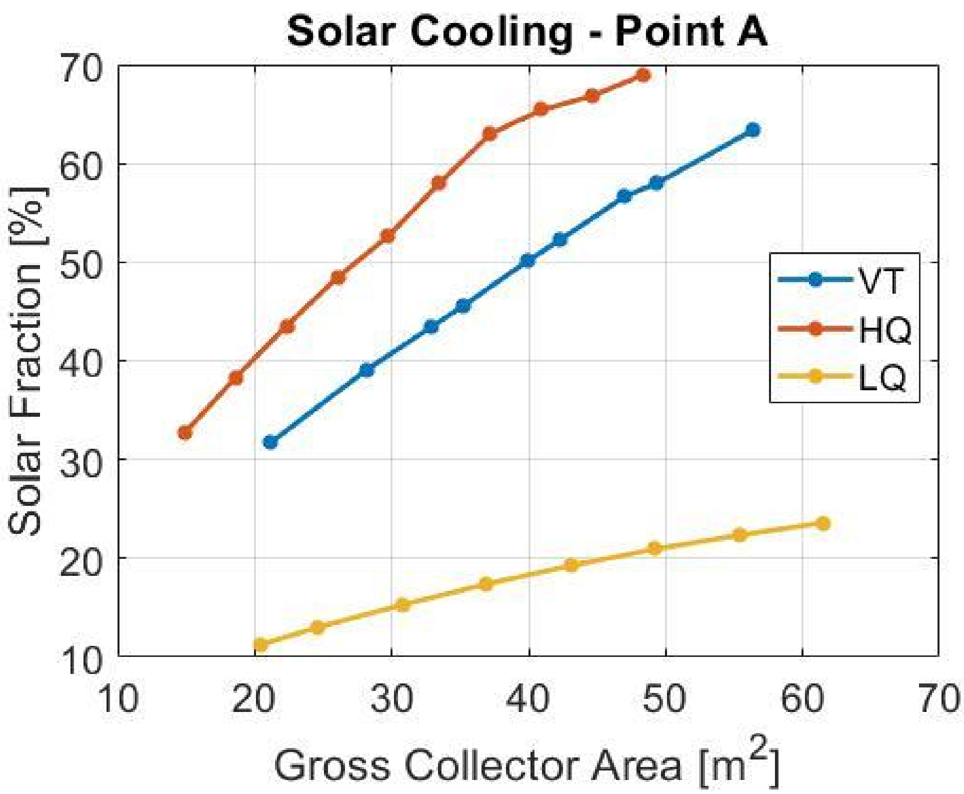

Figure 40 - Parametric analysis of SF with respect of collector area

The figure 40 shows that for High Quality collectors and Vacuum Tube collectors the values of the Solar Factor have the same trends, with HQ collectors reaching higher levels.

For the Low Quality collectors there is a slight increase of the SF with the increasing area; the SF however doesn't reach the value of 30 %.
We can justify this phenomenon by considering the hot water temperature for regeneration and its availability: in general High Quality collectors produce water at higher temperature and present lower losses.
Also Vacuum Tube technology is applied because of the high level of maximum temperature. The performance differences between LQ collectors and HQ and VC are more evident.

It is interesting to investigate the phenomenon of stagnation. From the first analysis the temperature of stagnation is reached rarely through the summer months: our storage tanks for the three systems are over 2000 liters. In this second analysis stagnation is the reason why with flowrates lower than 50 lt/min we cannot satisfy both the cooling and heating demand, in fact it may seem strange that a lower flowrate brings this kind of problem but this is due to the stagnation phenomenon.

In particular, during summer months in a warm location like Barcelona the irradiance is very high, so the water flowing in the circuit and especially in the tank can reach high temperatures. When this phenomenon occurs the stratification in the tank is less visible, the water in it has a more homogeneous and high temperature. When the temperature of water at the outlet of the collectors is too high, the system shuts down to avoid overheating, at this point the flowrate in the collector's circuit goes to zero and the only system heating up water is the auxiliary.

Therefore with a smaller flow rate there is less water to warm up and so it is easier to reach the stagnation temperature at the outlet of the collectors, our demand was never satisfied because the flowrate in the collector circuit was zero and the auxiliary had to provide the whole power.

To have a high storage tank volume has helped with stagnation: it brings to have more energy stored and better conservation of the hot water from the collectors.

In the figure 41 there is an example of what happens in the circuit when there is stagnation, for a week in september:

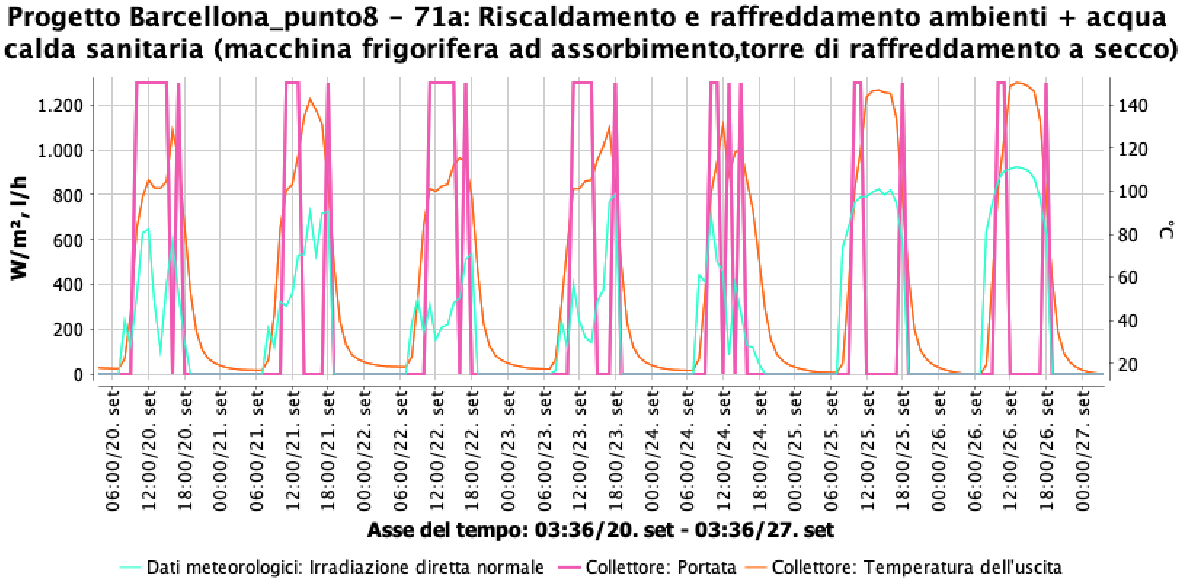

Figure 41 - Stagnation phenomenon

It is possible to see that when the temperature at the outlet of the collectors reaches a threshold value (in this case 120 °C) the flowrate immediately goes to zero.

Concerning the parametric analysis of the SF-area, we pay attention to the power deficit. The power deficit is the difference between the requested energy and the actual used energy by the consumers; the deficit shows us that sometimes the temperature requested by the consumer has not been reached.
For the summer months we notice that increasing the area the Q deficit decreases: if we enlarge the collectors area, it's simpler to provide a higher temperature at the outlet of the collectors.
Other factors can change the value of Q deficit. By increasing the requested setpoint temperature, the power deficit will decrease: the setpoint temperature will be quickly reached. If we consider a smaller tank volume, the stagnation phenomenon is more frequent than large tank: the cooling demand will be covered by increasing the auxiliary power, increasing consequently the power deficit.

POINT B
CALCULATION OF COP
The COP (Coefficient of Performance) of the system can be evaluated as:

$$COP = \eta collectors \cdot COPchiller$$

the efficiency of the collectors is computed as:

$$\eta collectors = \frac{Qsol}{H}$$

where:

- Qsol is the energy produced by the collectors [kWh]
- H is the energy provided by the Sun that hits the collectors [kWh]

Regarding the COP of the chiller, it can be calculated by performing a simple energy balance of a control volume, in particular the taken control volume comprises both the chiller itself and the vessel for the water storage, as shown in figure 42:

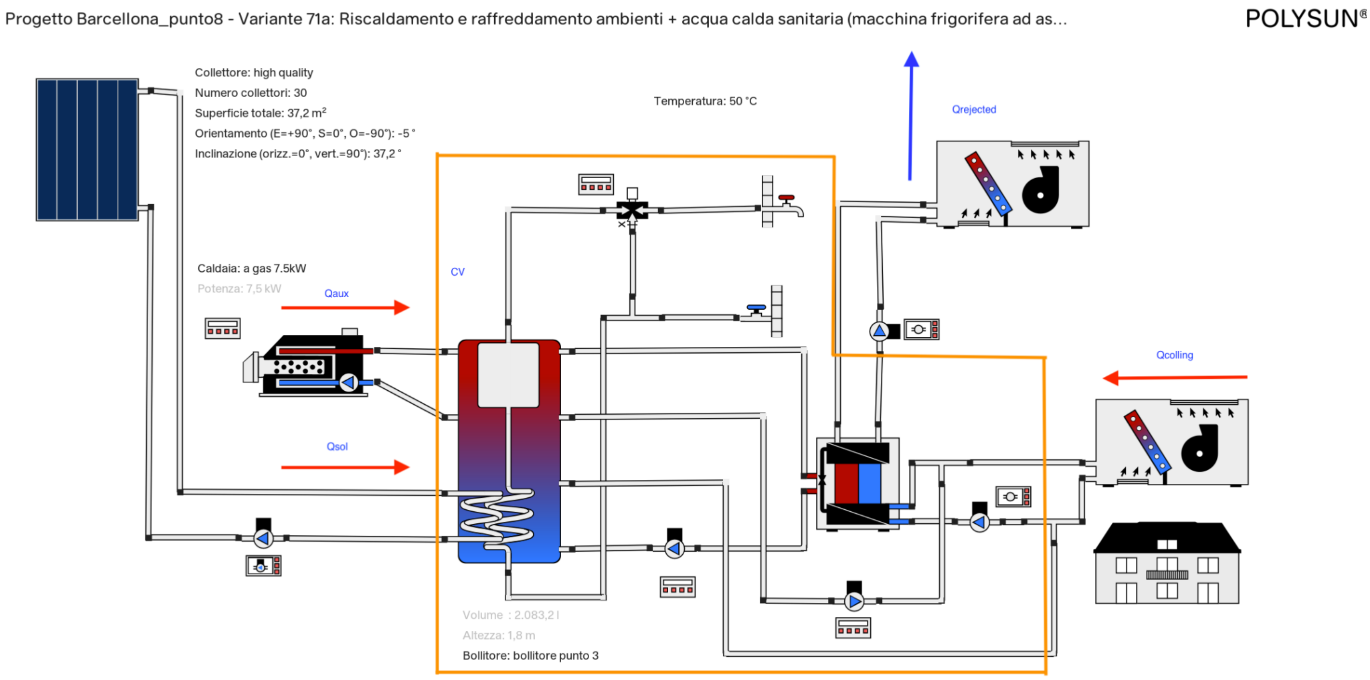

Figure 42 - Control volume and fluxes

The useful effect for us is the cooling energy, which is the energy removed from the house. In the picture the arrow representing Q cooling [kWh] is entering the control volume but in reality this energy has a negative sign, therefore we are removing it from the environment to cool down.

What we spend to obtain this positive effect is instead the summation of Q sol [kWh] and Q aux [kWh]. Q sol is the previously described energy, while Q aux is the energy provided to the water by the auxiliary when che collectors can not meet the energy demand. The arrows representing these energies are entering the control volume and have a positive sign.

Therefore we can compute the COP of the chiller as the ratio between the useful effect and what we consume to obtain it:

$$COPchiller = \frac{|Qcooling|}{Qsol + Qaux}$$

Theoretically we should also consider the energy exchanged between the working fluid (in this case air) and the pump that pumps it in the house. However this energy is assumed to be small with respect to the other contributions and therefore we consider it negligible.

The obtained results are summarized in the table 22 below:

Table 22 - COP for the three months

Months		Giu	Lug	Ago
Qc	kWh	-577.6	-1261.1	-1406.2
Qsol	kWh	1,490	2,532	2,504
Qaux	kWh	606	1,673	2,072
COP chiller		**0.276**	**0.300**	**0.307**
H	kWh	5,737	6,415	6,170
η collectors		**0.260**	**0.395**	**0.406**
COP global		**0.072**	**0.118**	**0.125**

The global COP has been computed for the summer months in which cooling is required, the needed energies can be found in the monthly dataset provided by POLYSUN.
A more accurate result could be provided using the hourly datas, in this way the COP could be calculated just for the times in which the collectors flow rate is different from zero. However in our plant there is no significant amount of stagnation and the flow rate of the collectors doesn't go to zero very often, this is because of the massive storage tank of the system, so we can say that the monthly datas are just as precise as the hourly ones.

A comparison has been made between the COP previously calculated and the one computed with the COP of the chiller provided by the software POLYSUN:

$$COPpolysun = \eta collectors \cdot COPchiller, polysun$$

where:

- η of the collectors is computed in the same way as before
- COP chiller,polysun = 0.57

The comparison between the COP with the two different approaches is shown in the table 23 below:

Table 23 - Comparison of COP

Months	Giu	Lug	Ago
COP global	**0.072**	**0.118**	**0.125**
COP global POLYSUN	**0.148**	**0.225**	**0.231**

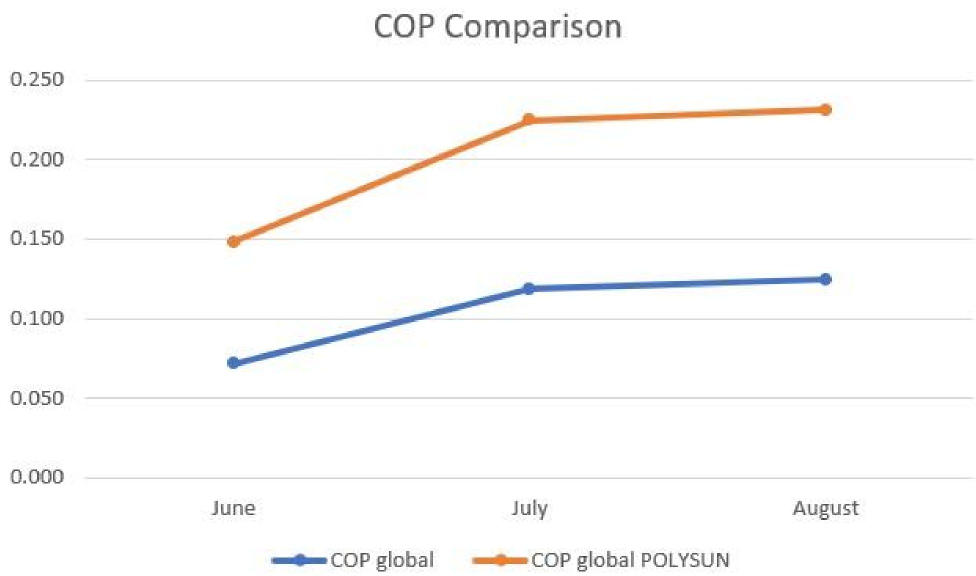

Figure 43 - COP global VS COP global, POLYSUN

As shown in figure 43 the trend of the different sets of values is the same, in fact the higher COP remains the one of August, the middle one is always the one of July and the lower is the one of June which has a significant drop with respect to the other two values that are nearer between them.

The second COP computed has higher values with respect to the first one. This may be because the value of the COP of the chiller provided by POLYSUN does not take into account the energy given by the auxiliary, therefore the energy spent to cool down the house is not the summation of the two contributions (Q sol + Q aux) but is just the energy granted by the collectors.
Being these energies spent and not a useful effect, they are at the denominator, so a smaller denominator gives us a higher ratio, which is the COP.

Another thing to point out is that the global COP could be also calculated considering an ideal cycle, applying the second law of thermodynamics we obtain:

$$COPideal = \frac{Tc \;\; Th-Tm}{Th \;\; Tm-Tc}$$

It depends on:
- Tc which is the temperature of the cold source
- Th which is the temperature of the hot source
- Tm which is the intermediate temperature level at which heat is rejected to the outdoor environment, through a cooling tower.

Of course we did not use this COP for our analysis because it is an ideal formulation and there are too many approximations to make, however we can derive some useful information such as that the COP increases with increasing Tc and Th and decreasing Tm.

POINT C
After finding the COP values, we improved our system. We decided to perform this analysis using the High Quality Collector because based on point A, it is the one with the highest Solar Factor. The specific characteristic of the HQ configuration should allow the improvement process to result in a sensible increase in performances, at least more than the LQ system.
First of all we decided to change the set point temperature values and then we changed the number of fan coils in the house and in the cooling tower to find the minimum value that would satisfy the cooling demand.
The output for the previous analysis is used as input for the following one.

1. **Set Point Temperature**

We have changed the value of the temperature required inside the house. We have compared the various Q deficits supplied by POLYSUN with the variation of the set point temperature.

As shown in figure 44, the Q deficit decreases with increasing temperature, so we have chosen 21 °C as the set point temperature value to have a good compromise between efficiency (low Qdef) and livability.

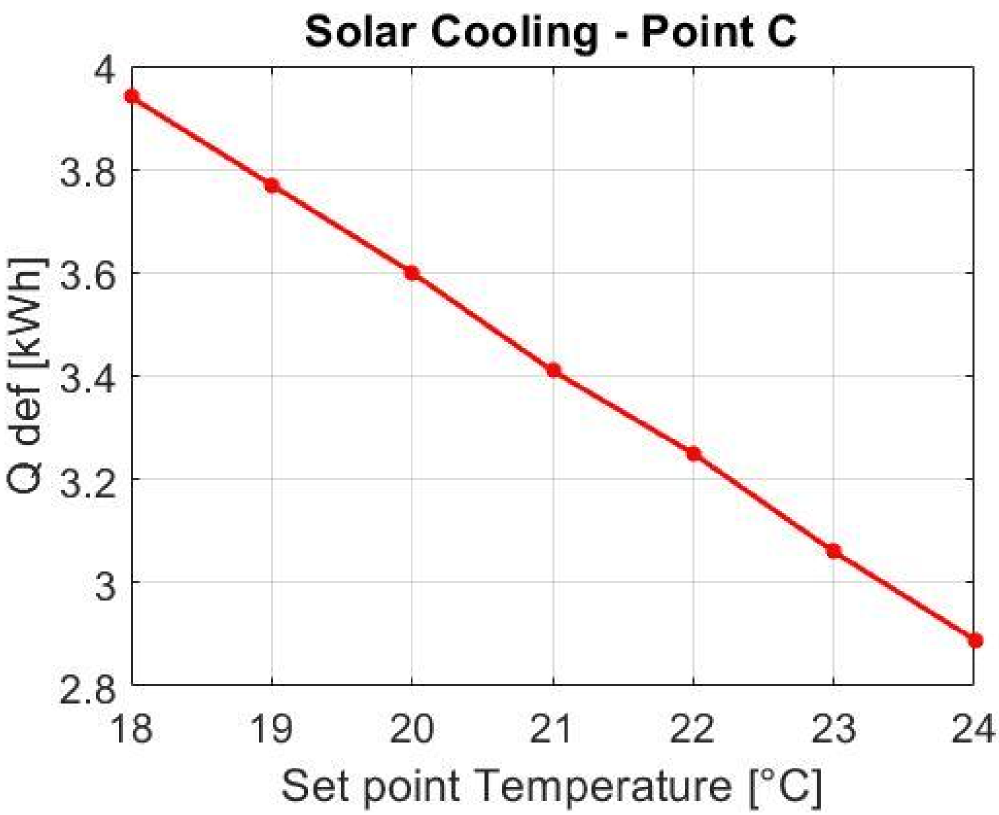

Figure 44 - Set point temperature VS Q def

2. **Number of fan coils at the evaporative tower and number of fan coils inside the house:**

In this case the increase in number of fan coils should allow to dissipate more heat at a lower temperature. But this advantage is limited by the higher cost, bulk and electrical consumption of this kind of plant. A high number of components does not cover costs and increases consumption from the auxiliary.

We set the temperature of the house at 21°C anche we change the different number of fan coils in order to find the minimum that satisfies the cooling request. We compared the values relating to the average Solar Factor of the summer months (June, July and August)
In table 24 we have respected the proportion between the fan coil numbers suggested by POLYSUN.
Table 24 - SF Vs number of fan coils

House	Tower	June	July	August	SF
6	10	60,131	47,564	43,721	**50,37**
5	9	63,113	51,671	47,904	**54,13**
4	8	60,064	49,389	45,42	**51,53**
3	7	60,841	47,449	42,636	**50,19**
2	6				requirement not met

We have found that the minimum demand is optimal with 3 fan coils for the house and 7 for the cooling tower, thus saving in cost.
In this configuration we get the maximum Solar Factor for 5 fan coils at the house and 9 at the cooling tower, but compared to the 12-20 used so far we have decreased the SF from 63 to 54.

Now we have decided to compare the different summer Solar Factor by keeping the sum of the fan coils fixed at 10. (Table 25)

Table 25 - SF Vs number of fan coils

House	Tower	June	July	August	SF
5	5				requirement not met
4	6	59,052	46,321	43,529	**49,53**
3	7	60,841	47,449	42,636	**50,19**
2	8				requirement not met

Keeping the total number of fan coils fixed at 10 and varying the number of fan coils between house and tower, we note that configuration 3-7 is the best configuration.
It is better to keep the proportion of the program with a greater number of fan coils at the tower.

Lastly we decide to keep the number of fan coils at the house fixed at 3 and we look for the minimum at the tower. (Table 26)

Table 26 - SF Vs number of fan coils

House	Tower	June	July	August	SF
3	3				requirement not met
3	4				requirement not met
3	5				requirement not met
3	6	54,849	45,175	41,487	**47,09**
3	7	60,841	47,449	43,636	**50,19**

Keeping the number of fan coils in the house fixed at 3, we note that the requirement is reached at a minimum with 6 fan coils at the cooling tower.
The configuration 3-6 is the best combination to reduce the number of fan coils.
The configuration 3-7 is the best combination keeping the POLYSUN proportion.

If our building is efficient enough and it is located in a very hot place in the summer period, as in our case in Barcelona, the number of fan coils inside the house will be lower than the number of units needed to reject heat to the outside.

CONCLUSIONS

Barcelona is a very sunny location: this has allowed us to reach very high levels of Solar Factor. Even though the Vacuum Tube collectors present good levels for Solar Factor, High Quality collectors are found to be the most efficient, with the highest SF values. The Solar Factor results in Low Quality collectors are the lowest in the analysis.

In the comparison between the various panels in the extent of SF as the area varies, HQ is the type of panel that achieves excellent efficiency, a higher SF with a smaller area. In this analysis we found a plateau and for this reason it is useless to add collectors.

In order to find the optimal tilt and orientation angles, we performed a conjugate analysis: it consists in varying one parameter fixing the other and vice versa, until their values remain stable. From this analysis we found values between 36° and 38° for the tilt angle and -2° and -8° for the orientation angle. About this last parameter we can say that its value is not exactly zero because of the weather and other issues that can provide shading on the collectors.

The optimal volumes for our storage tank are quite high, more than 2000 litres. We are aware that storages of this size are difficult to fit and in general more expensive, but this storage size allows us to avoid the stagnation phenomenon.

Regarding the improvement with the two tanks, we can say that the Solar Factor increases because since we have less water in the tanks, this water is warmer and also because in the second tank (the one which feeds the house) there are no cold sources. Anyway we have to consider that this configuration is costly with respect to the base case and also more space for the tanks is needed.
For the second improvement we tried to increase the flow rate. We found that for flow rates higher than 60 the Solar Factor does not increase anymore and there is a plateau, therefore

it is not convenient to further increase the flow rate also because the pressure in the pipelines may be too high and the water may spill.

The economical assignment consists of the evaluation of the Net Present Value for the three models and the Pay Back time, assuming 20 years for the analysis. We considered high initial costs for Vacuum Tube and High Quality collectors, while Low Quality collectors have lowest initial costs: the lowest Pay Back time is reached by the LQ collectors plant for 9 years. It is followed by the HQ collectors plant for 10 years and at last the VT collectors plant for 13 years. It is obvious that the choice of LQ is the best in this case: despite having worse efficiency, the time of investment return is the lowest.
We investigated moreover different scenarios of economics and energy market for the VT case: in case of a huge crisis in the energy sector, it is not convenient to build a collector plant. In fact the energy interest rate would be zero or negative values and the NPV doesn't reach the zero value neither after analysis twenty years.

In order to improve the standard of the building, solar cooling is investigated for our house. We concentrate on the summer months of June, July and August: for a more interesting and deep application we can study this technology also for May and September. We performed the parametric analysis of the SF as a function of the collectors area, expecting that the SF rises increasing the area. We obtain high values for HQ and VT collectors, reaching levels higher than 60% with the same function trends. In the case of the LQ collectors the SF has a similar trend but with slight rise at the increasing of the area: the values of SF don't reach 30%. We conclude that for this kind of plant, higher temperatures are reached if losses are low: the difference between the quality of the collectors is more evident.

It is possible to evaluate the performance of our plant by calculating the COP efficiency. Between the different methods, we decided to apply the formula

$$COP = \eta collectors \cdot COPchiller$$

because it considers solar cooling with the auxiliary and the solar contribute and the efficiency of the collector depending on irradiance. The results for the High Quality collectors for the summer months are included between the values of 0.07 and 0.13. The software POLYSUN already provides a COP for the chiller: in this case the global COP with the POLYSUN software is higher because it doesn't consider the auxiliary contribution.

For the improvements in the solar cooling part, we have firstly decided to change the temperature inside the house. We found an optimal set point value of 21 °C as a planning choice, in order to have a compromise between efficiency (low values of Q deficit) and liveability.
Finally we changed the number of fan coils both in the house and in the cooling tower, in order to find the minimum number that would satisfy the request. Our optimal configuration is 3 fan coils at the house and 6 at the cooling tower. For our sunny location the number of tower fan coils is higher than the internal one, because it requires more heat exchange with the environment: if the house is efficient, we need few fan coils in the internal part.

We can conclude that our best solution is composed of High Quality collectors with large volume tank: the collectors provide high Solar Factor while the large storage volume avoids stagnation phenomenon. The Pay Back time is 10 years, a good compromise between Low Quality and Vacuum Tube collectors. Considering the solar cooling plant, the COP reaches the highest values for High Quality collectors and the improvement analysis shows that the perfect setpoint temperature is 21°C.