POLITECNICO DI TORINO

Collegio di Ingegneria Energetica

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Tesi di Laurea Magistrale

Energy management Optimization of a PV System connected to a local grid in an office building

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1- INTRODUCTION

1.1 Background

The purpose of this project is to study, from a preliminary point of view, the management of a potential PV system, to be built in an office building of the Campus Sescelades of the university URV, located in Tarragona (Spain).

The office building on which the PV plant should be installed is reported in Fig.1, in which is reported the location of the site.

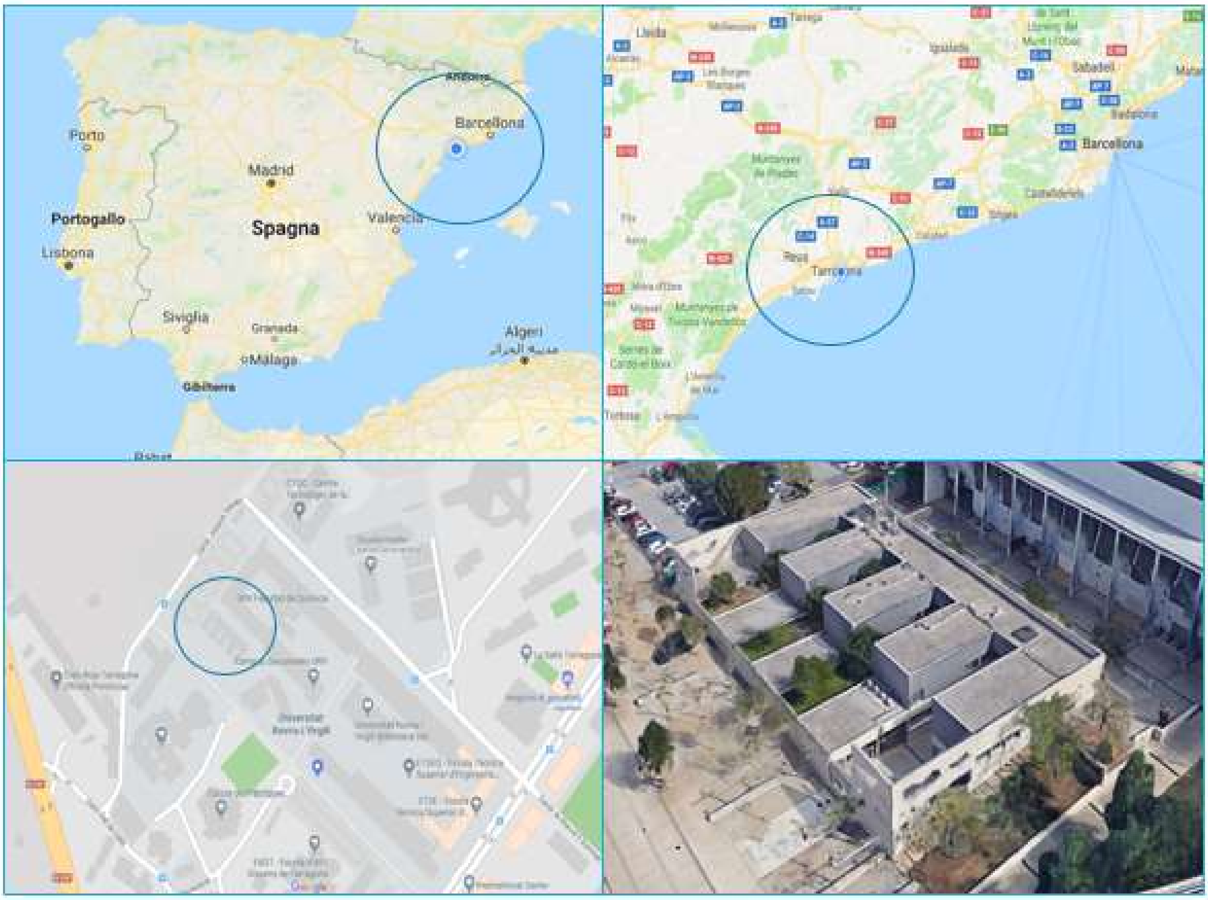

Figure 1: Location of the office building purposed for the PV plant

As reported in [1] this office building is named Building N2 SRCiT (Servei de Recursos Cientìfics i Tècnics) and it is used for providing support to the research groups of the university, both in terms of equipment and human resources.

Nowadays, this building is used and during the whole year is subjected to a certain electric demand due to the lighting system, the computers, laboratory equipment. Besides, a thermal demand must be satisfied, to ensure thermal comfort for the people working.

The building follows the same opening days of the rest of the university and is used all the weekday, so weekends are excluded.

The electricity needed during the whole year has been recorded within the last years from 2013 to 2017, hour by hour. So in [2], provided as initial data, is possible to find all the information related to its electric needs. In Fig.2 is reported the electricity consumption for the year 2017 and these values will be assumed as initial data for developing the project, while in Table 1 is reported a resume of the needs. Nowadays the electricity need is satisfied by the electric local grid, so the university must buy electricity from to grid, spending a certain amount of money every year.

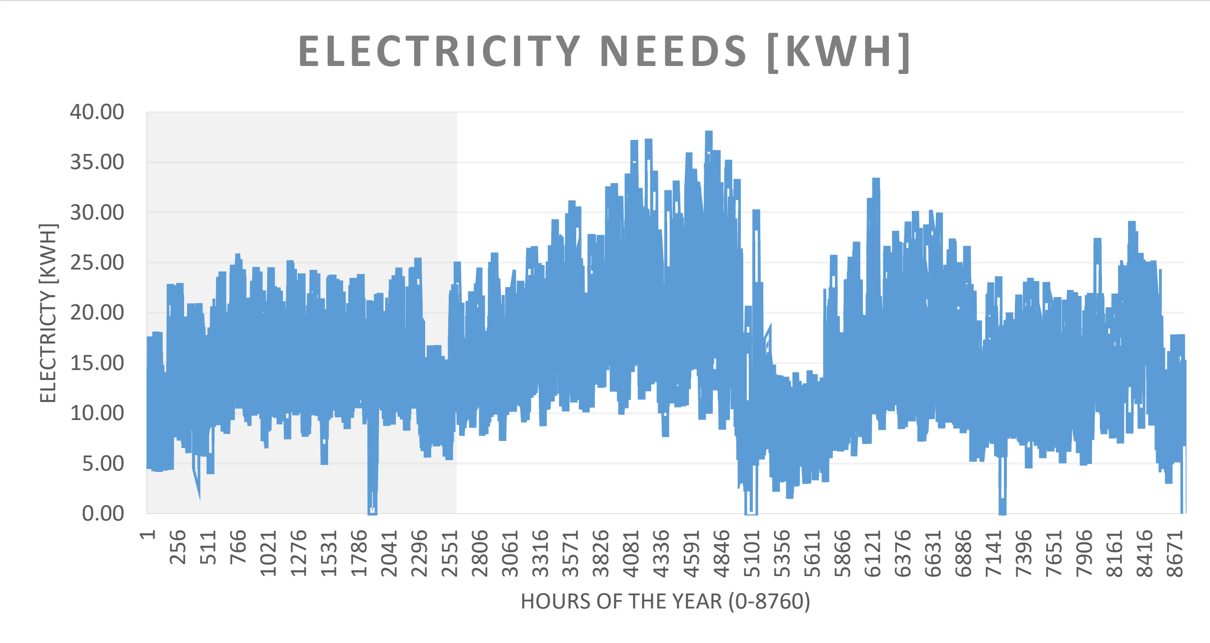

Figure 2: The electricity recorded in 2017

	US SRCiT N2 T Lab Recerca+Despatx [kWh]
TOTAL	120'398.30
AVERAGE	15.02
MEDIAN	14.50
MAX	35.83
MIN	0.06

Table 1: Resume of the electric consumption

For what concerns the thermal needs, now is satisfied using a water pipeline, connected to the building next to it, from a local thermal grid so, in which happens the production of heat and cool, not simultaneously, but separately, in concomitance with the different seasons of the year. The water flowrate satisfies the thermal demand with fan coils, located inside the building.

The thermal needs were not measured, but are the result of a process of simulation using the software Energy Plus, from the final project of a Grade student [3]. From this work, after the process of the simulation, appears that in some moments of the year is necessary both heat and cool, so the thermal power will be adapted to our scope, imposing a heating and a cooling season, in order to have certain periods of the year in which is necessary to heat or to cool only.

Fig.3 reports the adaptation of heating/cooling power necessary to be covered from the thermal system, as the result of the simulation, hour by hour, while table 2 resume the period of the year in which heating is provided, the period in which is necessary to cool and the period in which the thermal system is off.

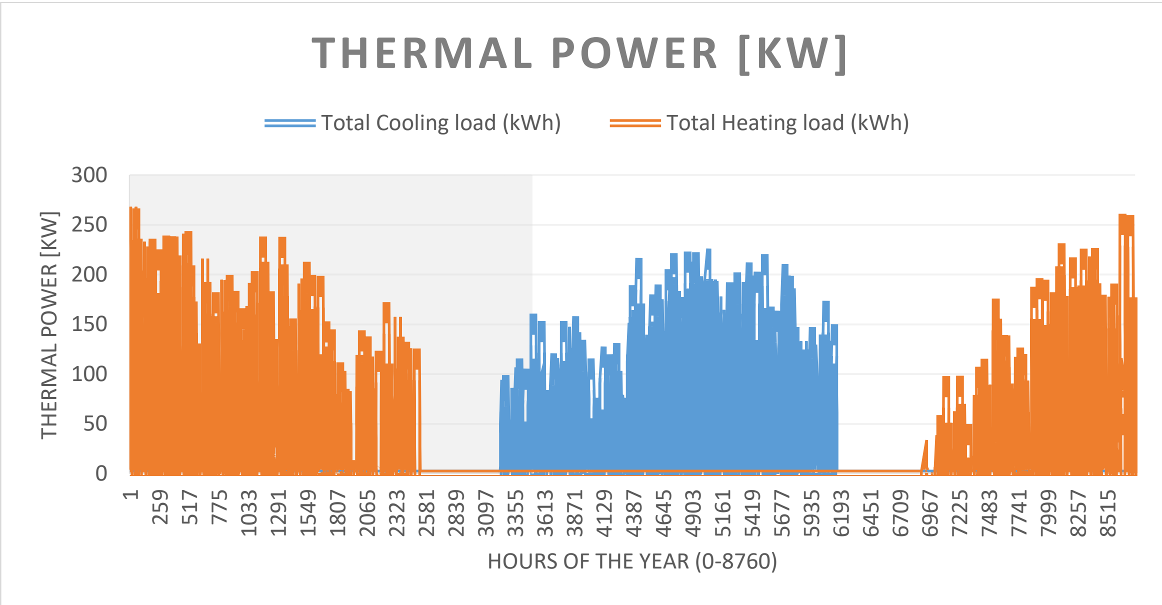

Figure 3: During the whole year is necessary to heat or to cool the office building

	Heating System	Cooling System
START DATE	15-ott	15-apr
STOP DATE	15-mar	15-set
MAX POWER [kW]	268	195
MIN POWER [kW]	0	0

Table 2: Resume of the seasonal thermal demand

So, resuming, both the demands, thermal and electric, are now covered by local grids. A certain amount of electricity has to be bought from the Spanish electricity grid for covering the electrical needs and the cooling (with a chiller) and a certain amount of gas has to be bought from the Spanish gas grid, to provide heating using a furnace.

1.2 The Project and the Motivation

As already said, this work born with the idea to study preliminarily the project of a PV system that may be developed on the roof of the office building, to reduce the energy consumption. In fact, on the free area, until now unused, of the roof of the building can be developed the system, South – oriented.

This PV system is expected to be coupled with a reversible air to water heat pump/ chiller, with the main goal to use as the best as possible the solar renewable energy: in fact, the electricity provided from the PV plant can cover totally or partially the electrical and the thermal need (using the reversible heat pump), promoting as most as possible the self-consumption. Excess Energy, not used, can be stored in a battery or sold to the grid provider or sent to the local grid, while when the solar contribution is lower than the demand, electricity can be taken from the local grid, or from the battery, if provided.

The reversible heat pump will be connected to the local thermal system, that will be used as auxiliary system.

As the title of this job says, the final goal to be expected is the energy optimization of the system, in order to use as best as possible, the renewable solar energy, but also taking in account the economic aspect, considering the investment cost (InEx), the operation cost (OpEx) and the primary energy consumption (PEC).

1.3 The Aim and the objectives

To perform the energy management and optimization, multi objective analysis will be performed, comparing from one side the payback time of the investment and on the other hand the primary energy used, for different possible solution depending on different parameters that will affect the performance of the system (photovoltaic area, Capacities of heat pump, angles of incidence of modules…). But on the other hand, the idea of this work is not to suggest how the plant has to be size, but the develop a methodology for applying transient dynamic simulations in this context.

From the final analysis will not be possible to evaluate just one best solution: in fact, as [4] says as results of a multi objective analysis, different best solution can individuated in the so called Pareto Frontier. Fig. 4 reported an example of a multi objective analysis, the final result to be expected from this work.

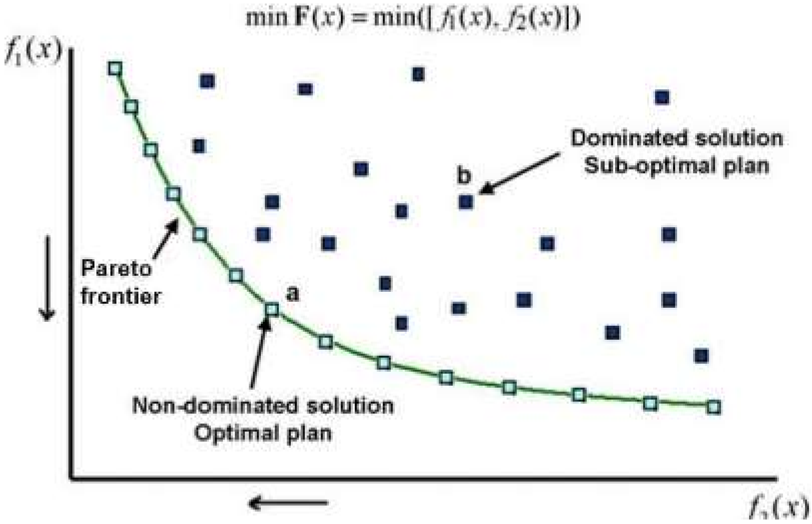

Figure 4: An example of a multi objective analysis (Di Somma, 2016)

Created the Pareto frontier, will be no possible anymore to define just one best solution, but will give us a good and immediate impact on what are the performance of the system compared to the cost and decide on this way which solution will be more affordable and reasonable, taking also in account environmental limits like CO2 emissions or initial expenditure capital available from the university. Fig. 5 explain the optimization problem.

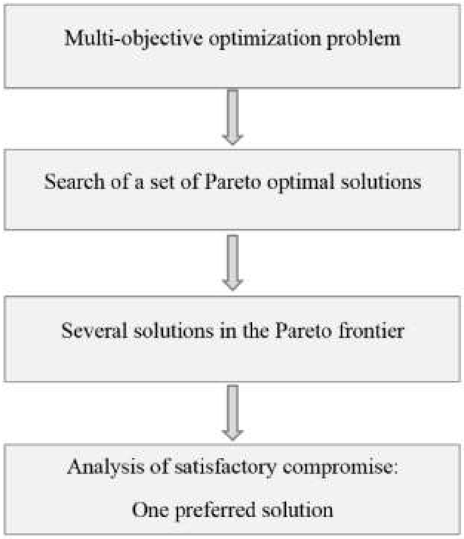

Figure 5: The path to be followed for a multi objective analysis (Di Somma, 2016)

So, to reach the final goal, is necessary to define specific objectives to be reached, taking advantage of software and skills that can help the resolution.

Particularly, first is necessary to understand what the thermal grid and the electric grid are and schematize them in a simple way, easy to be studied.

Later, to implement and develop this system in the TRNSYS software in such a way that should be easy to performs annual simulation and obtain the results wanted, to be studied in a post processing analysis with the multi objectives optimization.

In Fig.6 is resumed, and below is explained, the path that will be followed to get the result.

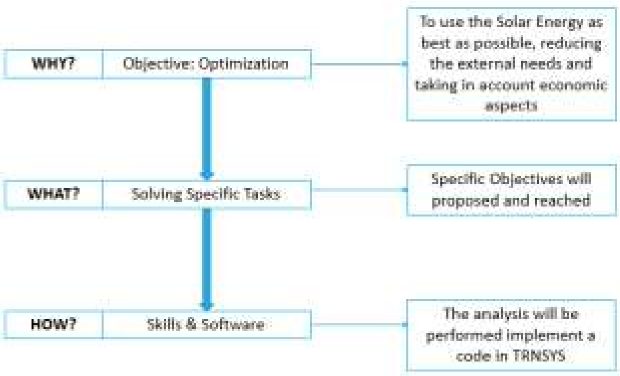

Figure 6: The Project resumed in few lines

The specific tasks are below described but will be treated in deep in the next session, in which will be reported step by step how will be possible to solve the specific tasks.

So, specific tasks will be achieved:

1) Analysis of the energy demand (thermal and electricity). Measuring the potential PV area.
2) Developing a suitable and simple scheme of the thermal and electricity local grid. Define which are the components already in the plant, the system used still now, and which new components are related to the creation of the PV plant.
3) Pre-sizing analysis: perform simple calculation to have initial value of PV area (m^2), Capacity of the chiller and heat pump (kW), angle of incidence (°). Find a real heat pump for this purpose.
4) Studying different possible controls that regulate the whole plant (inverter, temperature control, flowrate control…). Identify the control that will be used in this work.
5) Developing a complex and realistic model to be performed in TRNSYS, with the selected controls and validate it.
6) Simulation of the initial case, to evaluate the cost of energy before the project will be planned.
7) Perform sensitivity and parametric analysis evaluating how the plant changes its performance in terms of Energy Savings, Cost, Primary Energy Used, CO2 emissions, Payback time of the investment, varying the main parameters.
8) Post Processing: Multi Objectives analysis. Find possible non-dominated solutions.
9) Resume of the work with adequate conclusions and explanations.

1.4 Organization of the Thesis

Will be now described in some words how the thesis will be developed in the next pages:

- In chapter 2 will be reported in detail all the steps above resumed, solving the specific tasks purposed.
- In Chapter 3 The results of the process of simulation will be resumed and discussed, with the parametric analysis and the optimization.
- In Chapter 4 will be discussed if the goal proposed has been reached. Will be analysed weak points of the simulation and future works that could be performed.

- In Chapter 5 will be reported the references and the sources that have been useful for this work.

2- SIMULATION

2.1 Initial Analysis: Understanding the problem

This part will be treated quite shortly, because was partially described in the introduction, to explain the problem.

As already said, the building is subjected to thermal and electrical demand during the whole year. The electricity demand is always present, also during the night and during the weekends. The thermal demand is restricted to the university time schedule (work timetable) and is null during the weekends.

The thermal demand was adapted, modifying the initial data provided: in fact, is necessary to consider that the thermal grid is connected to the local thermal system, so is defined by certain period of heating/cooling during the year, considering that the terminals (fan coils) must work or in heating or cooling mode.

For what concern the location of the PV plant, in Fig.7 is reported again an image of the building. As already said, the PV plant is expected to be located on the roof, South oriented.

Figure 7: Site, Orientation and Potential area of Pv plant

The potential area measured with the software AUTOCAD is 900 m^2 on the horizontal. To this area will be necessary to remove the area needed from the battery (eventually), the inverter, the cables, the heat pump, the water pipeline: in this work the maximum area will be fixed at 750 m^2.

For what concern the inclination of the PV panel respect to the horizontal, the angle will be fixed at 30° for the pre-sizing analysis: in fact, as [5] report, between 20-40 ° for the angle of inclination of the PV plant, is reached the optimal angle to catch the maximum radiation from the sun. For the final parametric analysis, the incidence angle will be changed, to evaluate different performance during summer/winter period.

2.2 Developing a simple system

Is necessary to develop an intuitive model that can resume the real system.

Some assumptions have to be done:

- Will not analysed the system from an electrical point of view: just the management of the energy will be performed. It will be assumed that the cabling of the plant will be optimize later, on another level of study. As said, this a preliminary analysis, with the idea to provide motivation to elaborate in the next future a real feasibility study about it.
- The project to be developed forecasts the PV system coupled to a reversible air to water heat pump. So, the components that have to be included for the calculations, also for considering the investment cost, are the PV plant, the inverter, the battery, the heat pump. Later, the cost of work, the cabling, the water pipeline and so on, has to be included.
- Actually, the electricity is provided from the grid and the hot/cool water for the terminal systems are provided by the local thermal grid. Will be assumed that now the heating is provided with a gas furnace and the cooling with a chiller.

Fig.8 Schematize as the system is working now while Fig.9 represent the model developed and to be studied to reach the goal.

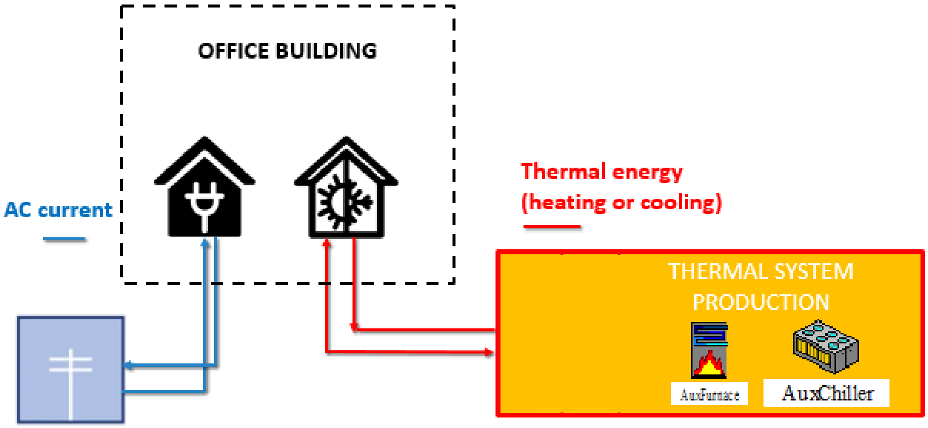

Figure 8: How the demands are provided now

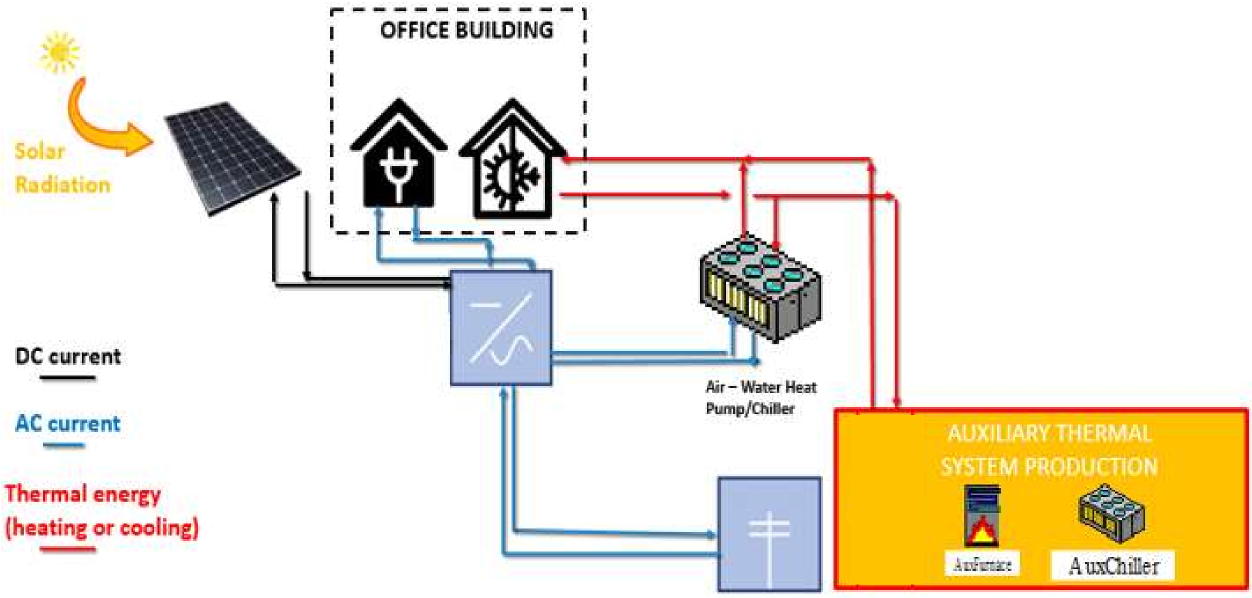

Figure 9: How the demands can be provided in the future

As is possible to see if Fig.9 the model proposed in this work include not only the PV system. In this case the furnace and the chiller used are considered auxiliary systems, because the objective is to use as more as possible the solar energy and will not be considered in the initial expenditure of the investment because are already present. The battery will not be considered in this work.

2.3 Pre-sizing Analysis

To develop the model on TRNSYS is necessary to evaluate data of pre-sizing.

For the pre-sizing of the PV area a simple model has been implemented in TRNSYS. Fig.10 shows the Pre-sizing scheme: Type9c contains the initial data of the thermal and electrical demand, while the component Type25c is an output file where will be written the data we want to obtain, month by month: Monthly Load (kWh), Monthly Radiation (kW/m2), Real hours of working (h), efficiency.

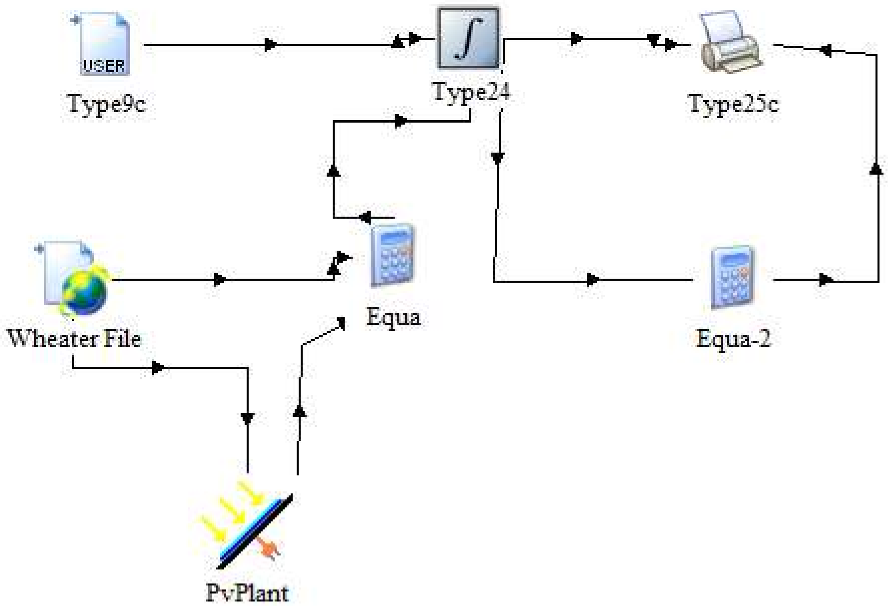

Figure 10: The Presizing model on TRNSYS

The PV module used is the one reported in Table 4, in which are the main data to be used as parameters in the TRNSYS component.

Bosch Solar Energy c-Si M 72 NA21126 290Wp	
Technology	mono - c- Si
η_{ref} [%]	14.8196%
G_{ref} [W/m2]	1000
Area [m2]	1.956
W_{peak} [Wdc]	289.972
$\delta W_{peak}/\delta T$ [W/°C]	-1.333
$\delta\ \eta_{ref}/\delta T$ [1/°C]	-0.00068

Table 3: The main PV characteristics

Table 4 report the technology of the module, mono crystalline silicon, the refence efficiency (at irradiance of 1000 W/m^2 and 25 °C), the module area, the peak power. The last two parameters report how the peak power and the reference efficiency change with changing the temperature.

To evaluate the pre-sizing PV area, will be evaluate the area that will be necessary to cover month by month the total electric consumption, considering that the thermal demand will be covered just with the heat pump/chiller coupled with the PV system, so without using the auxiliary thermal system. To do that is necessary to convert the thermal energy in electricity, passing through the COP for heating/cooling mode.

The formula 1 describes the main equation that has been used for this part: monthly, has been calculated the maximum area necessary to cover the whole consumption.

$$\eta_{pv,monthly} = \frac{Load,monthly\ [kWh]}{Month.Rad\ \left[\frac{kW}{m^2}\right] * Hours,monthly\ [h] * Area\ [m^2]} \tag{1}$$

The term *Load,monthly* is the total load of electricity needed each month, *Month,rad* is the average monthly radiation, just in the period in which the radiation is quite enough to produce electricity and the term *Hours,monthly* are the hours of the week in which this happens.

Having monthly the area, the lowest during the whole year has been chosen.

The month in which the lowest area has been evaluated is in April, with a value of 454 m^2, and this value will be used to evaluate the energy production and the relative solar factor of the PV system, as reported in fig.11.The peak of the demand happens in July.k

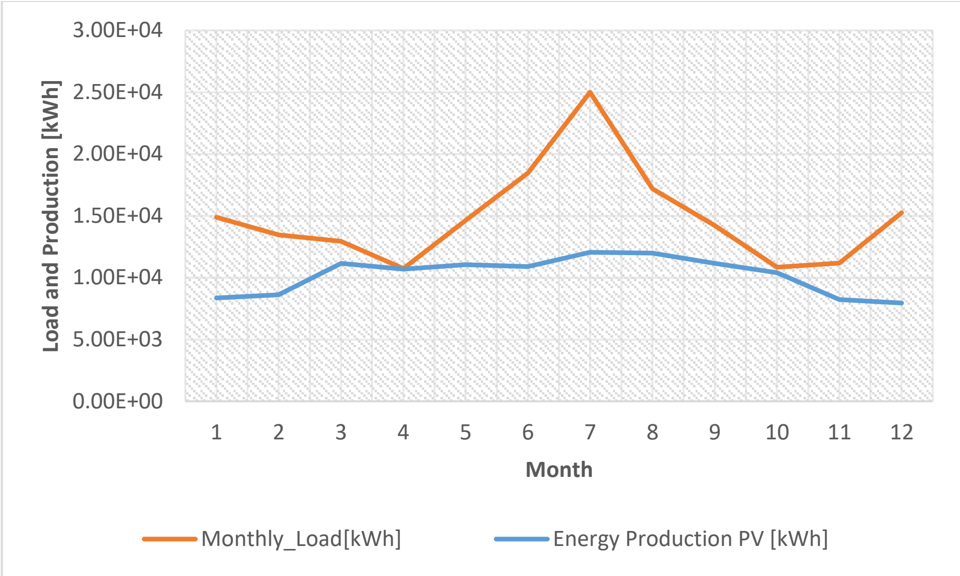

Figure 11: Load [kWh] vs PV production [kWh]

The area between the two lines is the part of the energy is not possible to cover with the PV plant, with an area of 454 m^2.

2.4 Control of the system

After defined the main initial data of the system, is necessary to define how the whole system is working, on the control levels. The scheme studied is the one of Fig.9. The control is applied on different levels:

1) Inverter: is necessary to define a strategy at the inverter. The idea purposed in this work is to provide all the electricity needed for lighting/computers with the PV plant or the grid if is necessary. The heat pump coupled with the PV will be turn on just if the PV production can partially cover the demand of its electricity, otherwise the auxiliary system will be used: Different heat pump capacity for heating/cooling of the PV coupled heat pump will be studied, in order to increase the fraction of renewable energy used. From now to the end of this work, will be referred as Load1 the load for the equipment/lighting and Load2 the electricity necessary for working the heat pump.
2) Seasonal Control: the heating/cooling period will be settled as initial data.

3) Temperature Control Set Point: Considering that the auxiliary system and PV coupled heat pump can work switching, has been decided to turn on the second just if the return temperature from the load is ±1°C compared to the set point temperature. This can happen if the load is very low, so the return temperature is quite the same of the inlet one. The mass flowrate is assumed constant, necessary to size the pump, too.
4) Flowrate Control: From the inverter an output control describes if the water flowrate passing through the load is coming from the auxiliary system or the PV heat pump or both. The control is done with 3 ways valves.

Fig.12 explain how the control is done on the inverter level. The idea is to create a series of condition that at each timestep can give us a binary output: 0 if the condition is not verified, otherwise 1. Different sceneries can be created and just one of these will be verified at each time step.

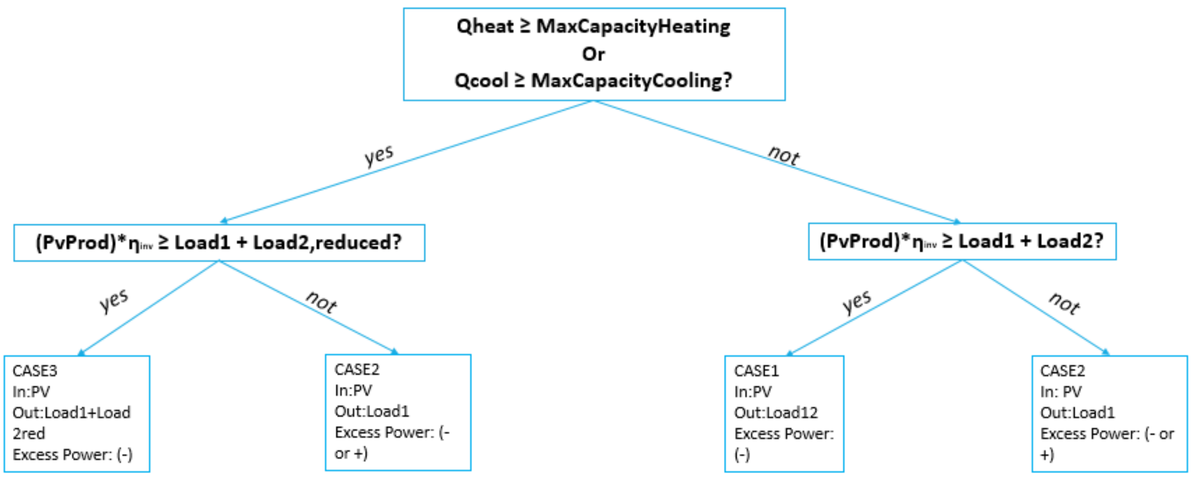

Figure 12:Control of the inverter

The idea of this control is so explained: first of all, is checked if the heat/cool required is higher than the maximum capacity of the heat pump: the maximum capacity depends on the temperature of the air entering as source and the inlet temperature of the water load. So, the maximum capacity is evaluated at each time step as the largest value between the reference value of the heat pump and the capacity at each previous timestep. If this condition is verified (left part of the scheme) this means that the heat pump selected cannot cover totally the thermal demand. So the thermal needs will be covered partially, until the maximum capacity: The term *Load2,reduced* means the electricity required to provide just that part of thermal demand.

Again, two different situations can happen: the PV production can or not cover the *Load1*and *Load2,reduced*. In the case is not verified, the thermal demand will be covered just by the auxiliary system, while the electric one will be covered by the PV plant or from the grid: in fact, the excess power in this case can be positive or negative, depending if the PV plant can cover the electrical demand or not.

The right part of the scheme is very similar, with the only difference that in this case the thermal demand is lower than the capacity, so, if the PV production is enough, the thermal demand can be just cover used the PV coupled heat pump. Table 5 resume the different cases of the control:

Control Case	Input Power [kW]	Output Power [kW]	Excess Power to the electric local grid [kW]	Heat Pump Mode	Auxiliary Mode	FlowRate Control on 3 ways valve (respect to the auxiliary system)
CASE 1	PV	Load1+Load2	To Local Grid (-)	ON	OFF	0
CASE 2	PV	Load1	To (-) or From (+) Local Grid	OFF	ON	1
CASE 3	PV	Load1+Load2red	To Local Grid (-)	ON	ON	from 0 to 1

Table 4: Different Output Cases from the inverter

For what concern the seasonal control, it has just settled with a simple time control. Will be possible easily to change the season length if will be requested to investigate a similar project in another location.

The temperature set point control is necessary because in the model of the reversible heat pump, that will be explained in the next part, is not possible to fix a set point temperature. This means that, depending on the external temperature, with a fixed flowrate of water, the capacity of the heat pump and the COP is changing and the temperature of the water exiting from the heat pump and entering to the terminals of the building, could be some degrees more than the set point desired. On the other hand, the set point control is in fact imposed on the temperature of the water returning from the load: if it is ±1°C of the set point (55°C for heating, 7°C for cooling), the heat pump is not working, and the water will recirculate in the system.

Finally, for the flowrate control, is directly connected to the inverter control, that define as output, if is working the auxiliary system or the reversible coupled heat pump or both.

2.5 Developing on TRNSYS

Defined the control, will be possible to evaluate the model on TRNSYS and to validate it.

The main components that has been used to create, in TRNSYS, a model that is representative of the one of Fig.9, are reported in table 5.

Standard Component in TRNSYS and types		
Component Name	TRNSYS type	Main Parameters
Solar PV	562	Area [m2]; Reference PV Efficency [-]; Reference Temperature [°C]; Reference Radiation [W/m^2]; Efficency Modifier Temperature[1/°C]
Pipes	31	Inner diameter [m]; Pipe Lenght [m]; Fluid Density [kg/m^3]; Fluid Specific Heat [kJ/kgK]
Pump	3	Maximum Flowrate [kg/hr]; Fluid Specific Heat [kJ/kgK]; Maximum Power
Diverting Valve	647	Number of Outlet ports [-]
Mixing Valve	649	Number of Inlets [-]
Heat Pump (Pv Coupled)	668	Fluid Specific Heat [kJ/kgK]; Load Specific Heat [kJ/kgK]
Auxiliary Furnace	751	Rated Capacity [kW]; Fluid Specific Heat [kJ/kgK]
Auxiliary Chiller	655	Rated Capacity [kW]; Rated COP [-]; Fluid Specific Heat [kJ/kgK]

Table 5:Resuming of the component and types in TRNSYS

The heat pump models selected is reported in the Table 6.

Aermec ANL-H 290-650				
Version	290	400	580	650
Cool Capacity [kW]	53	78	101	122
Power[kW]	20.91	30.58	44.6	51.87
Heat Capacity [kW]	61	90	122	142
Power[kW]	18.82	28.44	38.73	46
Cost [€]	17634	24120	28676	31892

Table 6: The different PV coupled heat pumps studied

As already said, different models of heat pump are purposed, to study the effect of increasing the fraction of thermal demand that can be provided with renewable energy, avoiding the use of the auxiliary system. The data of the heat pumps are obtained from [6], [7].

The validation of the TRNSYS model has been performed evaluating the temperature and the flowrate, comparing it with the results expected from the control.

Figure 13 report the model elaborated in TRNSYS.

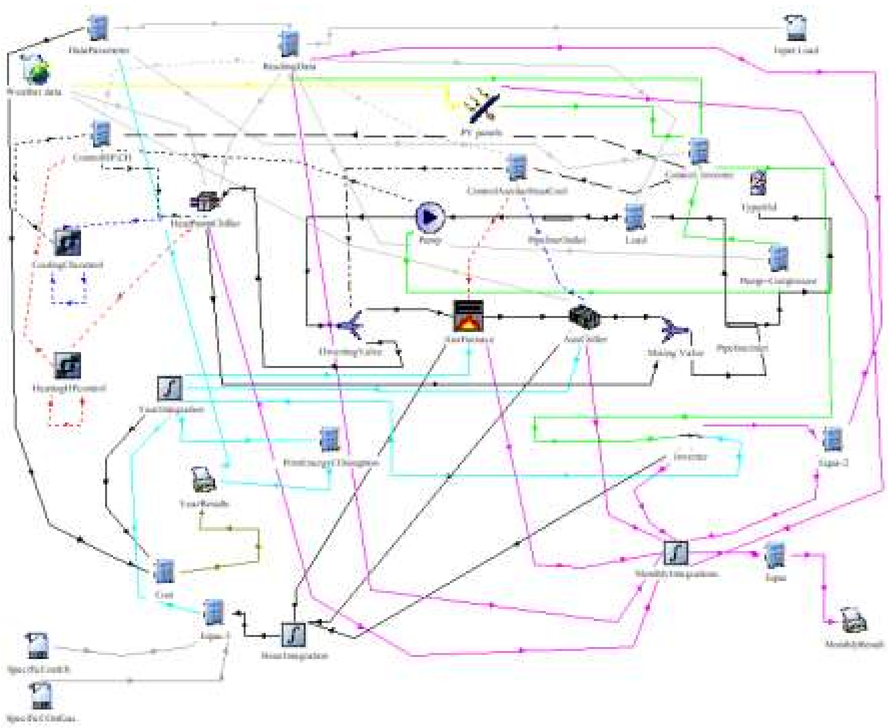

Figure 13: The model created on TRNSYS

2.6 Initial Case and First Simulation

First, to investigate future savings in term of cost and CO2 emissions is necessary to estimate how much is spending now from the university to buy electricity and gas from the national grid, to satisfy the needs.

For what concerns the specific cost of gas and electricity, these values have been provided from the university and reported in the tables below. Table 7 report the prices of the gas and the period of the day in which each period is defined. In our case the gas demand is only in the winter period, because is connected to the use of the furnace, not used in the summer.

Period	Winter	Summer	CostGas [€/kWh]
Peak – P1	18.00 -22.00	11.00 - 15.00	0.04759535
Mean – P2	8.00 - 18.00 / 22.00 - 24.00	8.00 - 11.00 - 15.00 -24.00	0.0513524
Low – P3	00.00 - 8.00	00.00 - 8.00	0.05546761

Table 7: Gas prices and periods

For what concerns the price of electricity, there are six different period prices, reported in the next table, Table 8, provided from the university, while Table 9 reports how the prices varies during the year, from [8]:

	Gen	Feb	Mar	Apr	Mag	Giu 1st half	Giu 2nd half	Lug	Ago	Set	Ott	Nov	Dic
P1	0.126893	0.128259	/	/	/	/	0.128259	0.128259	/	/	/	/	0.126893
P2	0.114896	0.116068	/	/	/	/	0.116068	0.116068	/	/	/	/	0.114896
P3	/	/	0.089602	/	/	0.089602	/	/	/	0.089602	/	0.089602	/
P4	/	/	0.085094	/	/	0.085094	/	/	/	0.085094	/	0.085094	/
P5	/	/	/	0.079756	0.093820	/	/	/	/		0.079756	/	/
P6	0.076183	0.084706	0.064103	0.067472	0.083115	0.083115	0.083115	0.083115	0.083115	0.083115	0.067472	0.064103	0.076183

Table 8: Different Prices of Electriciy. The numbers are expressed in €/kWh

	HORAS DE	HORAS A	ENERO	FEBRERO	MARZO	ABRIL	MAYO	IUNIO		JULIO	AGOSTO	SEPTIEMBRE	OCTUBRE	NOVIEMBRE	DICIEMBRE
DE LUNES A VIERNES	00	01	6	6	6	6	6	6	6	6	6	6	6	6	6
	01	02	6	6	6	6	6	6	6	6	6	6	6	6	6
	02	03	6	6	6	6	6	6	6	6	6	6	6	6	6
	03	04	6	6	6	6	6	6	6	6	6	6	6	6	6
	04	05	6	6	6	6	6	6	6	6	6	6	6	6	6
	05	06	6	6	6	6	6	6	6	6	6	6	6	6	6
	06	07	6	6	6	6	6	6	6	6	6	6	6	6	6
	07	08	6	6	6	6	6	6	6	6	6	6	6	6	6
	08	09	2	2	4	5	5	4	2	2	6	4	5	4	2
	09	10	2	2	4	5	5	3	2	2	6	3	5	4	2
	10	11	1	1	4	5	5	3	2	2	6	3	5	4	1
	11	12	1	1	4	5	5	3	1	1	6	3	5	4	1
	12	13	1	1	4	5	5	3	1	1	6	3	5	4	1
	13	14	2	2	4	5	5	3	1	1	6	3	5	4	2
	14	15	2	2	4	5	5	3	1	1	6	3	5	4	2
	15	16	2	2	4	5	5	4	1	1	6	4	5	4	2
	16	17	2	2	3	5	5	4	1	1	6	4	5	3	2
	17	18	2	2	3	5	5	4	1	1	6	4	5	3	2
	18	19	1	1	3	5	5	4	1	1	6	4	5	3	1
	19	20	1	1	3	5	5	4	2	2	6	4	5	3	1
	20	21	1	1	3	5	5	4	2	2	6	4	5	3	1
	21	22	2	2	3	5	5	4	2	2	6	4	5	3	2
	22	23	2	2	4	5	5	4	2	2	6	4	5	4	2
	23	00	2	2	4	5	5	4	2	2	6	4	5	4	2
SÁBADOS DOMINGOS Y FESTIVOS*			6	6	6	6	6	6	6	6	6	6	6	6	6
			6	6	6	6	6	6	6	6	6	6	6	6	6
			6	6	6	6	6	6	6	6	6	6	6	6	6
			ENERO	FEBRERO	MARZO	ABRIL	MAYO	IUNIO		JULIO	AGOSTO	SEPTIEMBRE	OCTUBRE	NOVIEMBRE	DICIEMBRE

Table 9: Different Cost Period of electricity, hour by hour.

So, has been simulated the initial case, without PV coupled heat pump and PV system. The result of the Primary energy consumed (PEC) each year, expressed in terms of kWh, and the Operation Expenditure (OpEx) in € are reported below, in Table 10. The OpEx is only due to the price of electricity and gas, while the PEC has been calculated using the relative conversion factor from [9], to have primary energy from the consumption of electricity and gas, such as the CO2 emission coefficients to have CO2 emissions in kg.

Initial Case	
PEC [kWh]	478209
CO2 Emission [kg]	115585
OpEx [€]	76817

Table 10: PEC, CO2 and OpEx of the initial Case

Later, has been performed an analysis with the pre-sizing data, using the version V400 of heat pump. The parameter of the first simulation are reported in Table 11.

PV[m2]	Slope[°]	Tset,cool [°C]	Tset,heat [°C]	CoolCap[kW]	HeatCap[kW]	VersionHP
450	30	7	50	78	90	400

Table 11: Presizing Parameter used in the 1st simulation introducing the PV plant

To calculate the cost related to the PV plant has been referred to [10], resumed in the table below, Table 12. The price of the PV module has been evaluated from the software "System Advisor Model" of NREL (National Renewable Energy Laboratory).

Price	Specific Cost	Unit
Module	0.55	€/Wdc
Inverter	0.10	€/Wdc
Structural&Elt Component	0.24	€/Wdc
Taxes, Labour, Inventory	70% of Investment	€
Maintenance	11.7	€/kWdc/year

Table 12: Prices related to The PV system

With this data, the 1^{st} simulation with the data of Table 11 can be performed.

Fig. 14 reports the solar factor, simple parameters that schematize the relationship between the renewable energy used and the energy needed by the loads. Formulas (2) and (3) describs how are evaluated these factors: the higher they are, the higher is the renewable energy used, avoiding external sources and reducing PEC. Both these parameters will be expressed monthly.

$$SF_{elt} = \frac{Elt_{load}[kWh] - Excess\ Energy\ [kWh]}{Elt_{load}[kWh]} \quad (2)$$

The electrical solar factor is expressed as the difference of the electric demand to be provided *Elt,load* and the *Excess Energy* at the inverter (positive is bought, negative if sold), divided the electrical demand. Can happens so that the Electrical solar factor can be more than 100% if the net energy to/from the grid is negative, so this factor has been limited to 100%.

For what concerns the thermal solar factor:

$$SF_{th} = \frac{Q_{PvCoupledHp}[kWh]}{Q_{load}[kWh]} \quad (3)$$

In this case is the relationship between the thermal energy provided from the PV coupled heat pump divided the demand. Is expected always to be lower than 100% because the PV coupled heat pump is not designed to cover always the thermal demand.

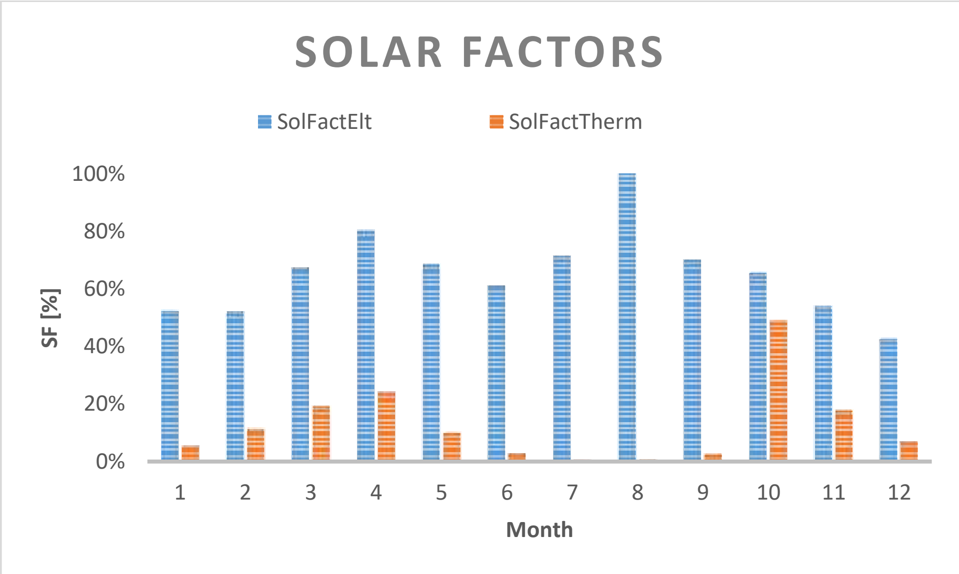

Figure 14: Solar Factor of the 1st Simulation

In the figure above is well expressed what happens with this pre-sizing data: for what concerns the electrical solar factor it reaches very high value, from 45% to 100%. The explanation of the peaks reached has to be find in the solar thermal factor: during the peak periods of the thermal demand (December and January, July and August) the PV coupled heat pump cannot cover it, because is not sized to cover totally the demand: a solution can be to increase the thermal capacity of the heat pump, passing to a larger version of the ones reported in Table 6.

However, in this case yearly result and first conclusions can be taken. Table 13 reports the PEC and CO2 emissions for this case. Also, are reported the Investment Expenditure (InEx), the OpEx and the money savings: in fact the difference between the amount of money to be payed from the university now and the money to be payed due to the OpEx (Cost of energy and maintenance of the PV plant) is as a matter of fact a saving, for the university expenditure.

1st Simulation		Reduction (%)
PEC [kWh]	241494	49.5
CO2 Emission [kg]	56992	50.7
OpEx [€]	26652	65.3

Saving [€]	50348	/
InEx[€]	142544	/

Figure 15: Yearly Results of the 1st simulation

As is possible to see, important results have been already provided about the possibility to create or not the PV plant: the PEC and the CO2 production has been reduced of the half respect to the initial case, with a gain every year of 50000 €, considering and investment of about 150000€. This means that in about 3 years, the investment done will return and the future savings of money can be considered a positive effect. Thinking that the PV plant is expected to work for 15-20 years, about 750000 – 1000000 € can be gained after this period, with a very positive effect.

However, to find the best solutions, is necessary to perform a parametric analysis, in order to do a multi-objective analysis.

2.7 Further simulations and sensitivity analysis

Is possible to investigate how the performance of the system change, changing some of the parameters.

An important parameter that will be useful for the result and simulation is the Payback time, so the time after that the plant start to have just positive benefits and the amount of money invested has been already reimbursed.

The payback time (PBT) is defined as time in which the net present value (NPV or VAN) is zero, defined in formula (4):

$$NPV = -C_0 + \sum_{i=1}^{n} \frac{C_n}{(1+i)^n} \qquad (4)$$

Where C_0 is the initial cost of investment, while Cn is the operation expenditure of each year, considering evaluating the saving deriving the positive effect from the less amount of energy and the negative effect due to the maintenance of the PV system, considered a certain rate of discount i, fixed at 3% as reported in [11].

Different simulations have been performed, varying the heat pump model, the PV area and angle of incidence.

In the next figures is reported the effect on the PEC, Payback time and OpEx, varying the angle of incidence, using a certain heat pump. As is possible to see in Figures 14, 15, 16 no significant effect on the incidence angle is reported:

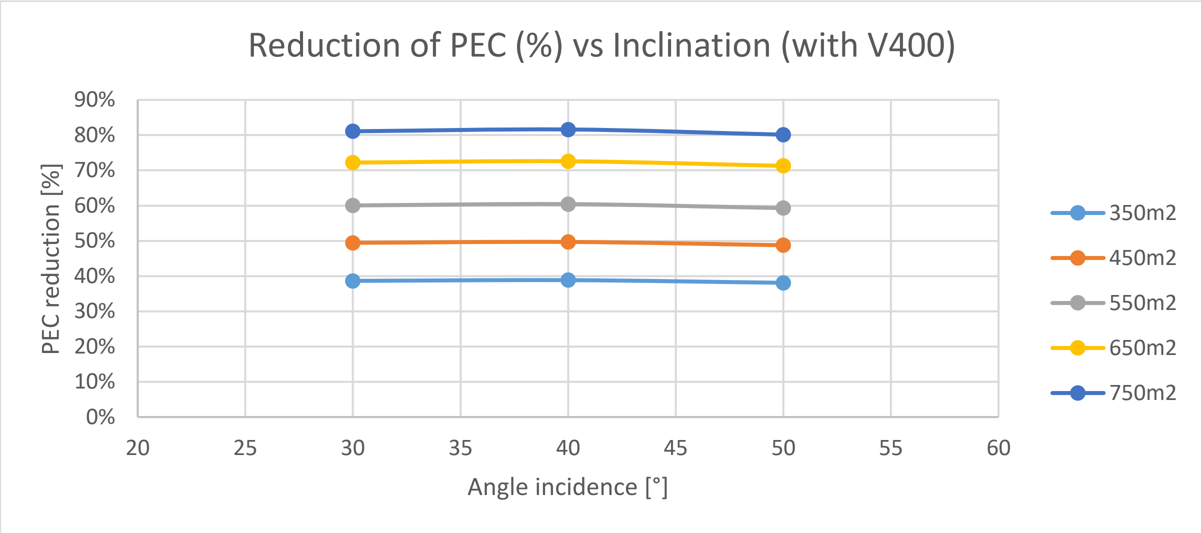

Figure 16: Percentage reduction of PEC respect to the initial case

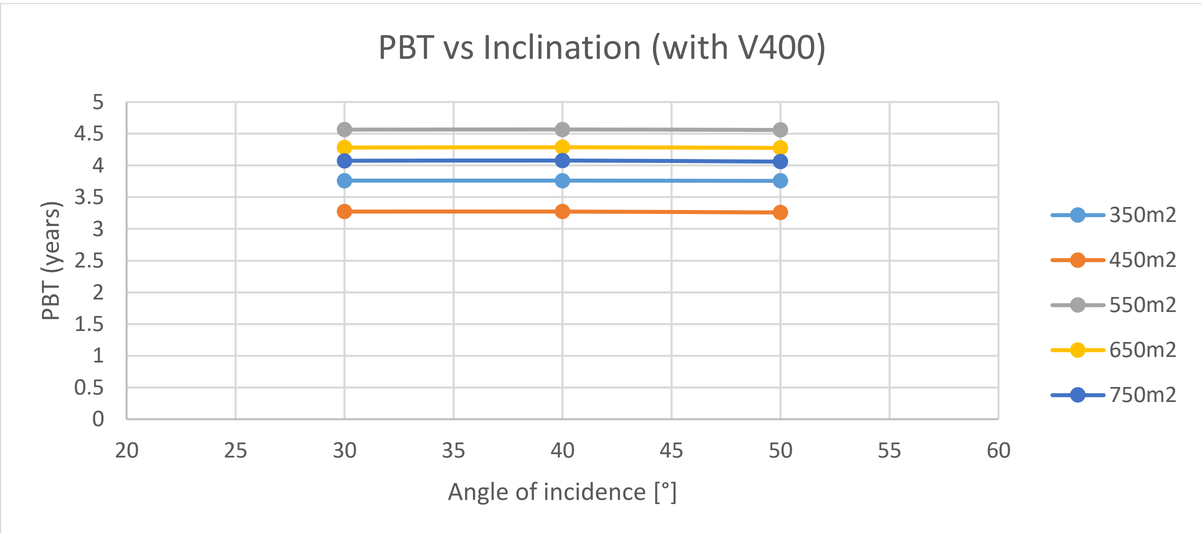

Figure 17: PBT vs Angle of incidence

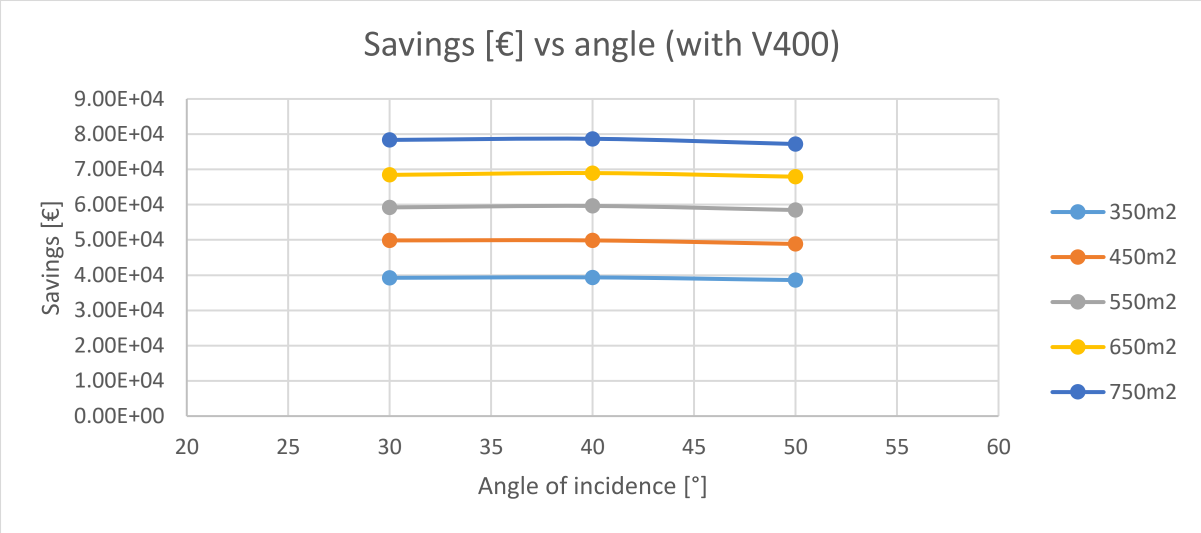

Figure 18: Savings [€] vs angle of incidence

As is possible to see, with the same heat pump used, for different areas and angle of incidence, no differences result.

So, is possible to evaluate the effect of using different heat pump models and areas, with a fixed angle of incidence, as reported in Figures 19, 20, 21:

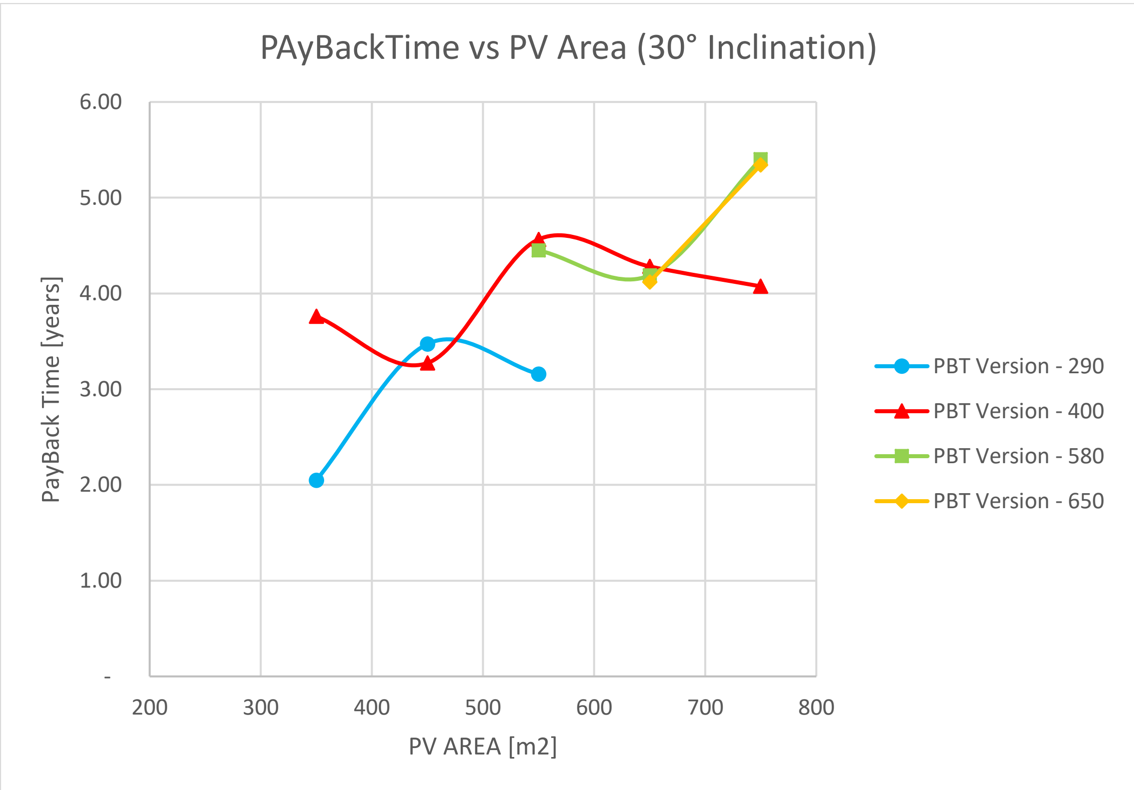

Figure 19: PBT vs Area

Is possible to see in Fig. 19 that the PBT vary from 2 to 5 years more or less, depending on the area and on the model of heat pump

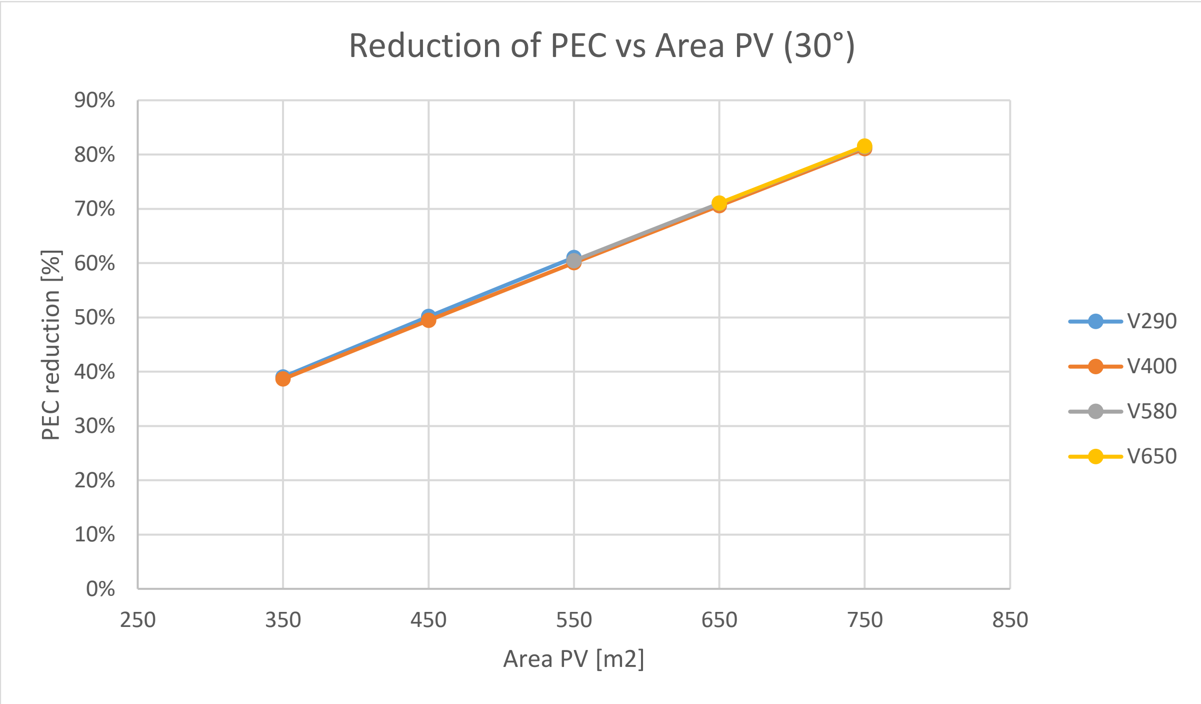

Figure 20: PEC reduction [%] respect to the initial case

As is possible to see in Fig.20, again the changes depend so much from the area, but a reduction of 80% of primary energy can be reached with a plant of 750 m2. The costs of investment and the operation costs are reported in the next graph, in Fig.21: is possible to see that are related: at the same area, for different heat pump, the differences in the InEx are due to the different cost of the model of heat pump, while the operation cost decreases increasing the area, thanks to the lower amount of primary energy needed.

So, the idea of this sensitivity analysis was to investigate which are the parameters that affect more than others the PEC and the cost and the result is that he variation are due especially due to the area, just a bit from the different model of heat pump and angle of incidence.

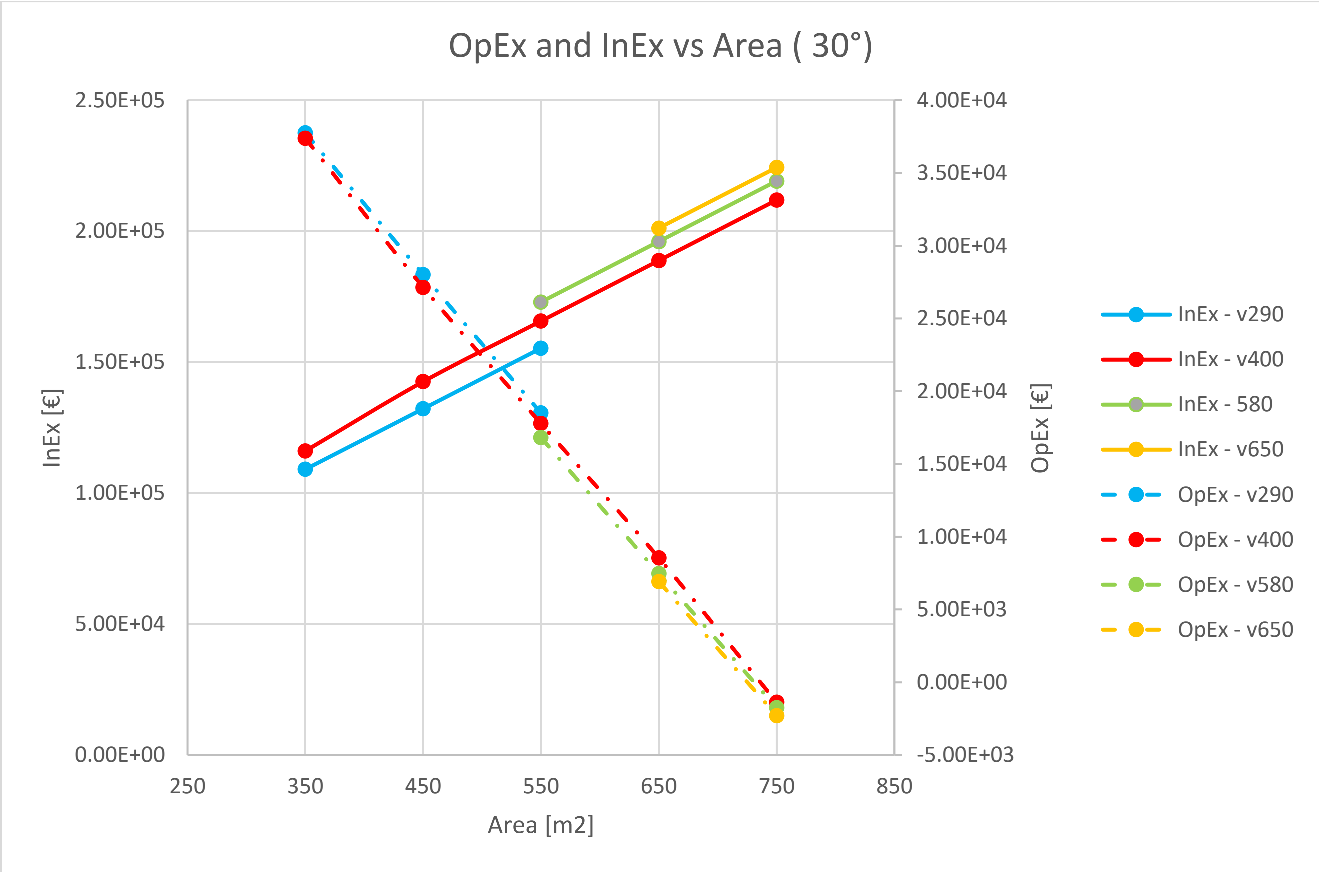

Figure 21: OpEx and InEx vs PV area [m2]:

3- RESULTS AND DISCUSSION

3.1 Multi Objective Analysis

As said at the beginning of this work, the idea is to perform a multi objective analysis creating a Pareto and find some best solutions.

To do it is necessary to perform different simulation in order to have the data needed.

Fig.22 reports the data obtained:

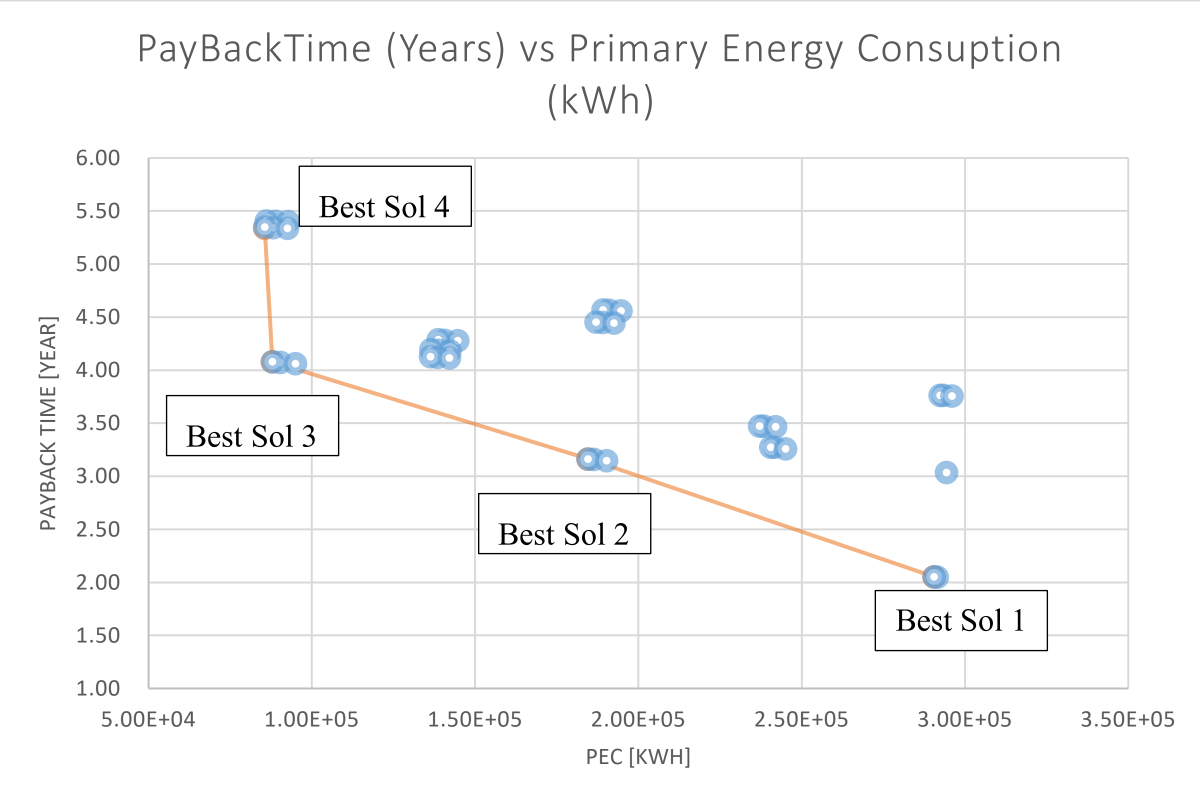

Figure 22: Multiobjective analysis

The orange line defines the Pareto and so after this analysis four best solution has been found, the ones placed on the line and resumed in the next table:

Best Solution	PV[m2]	Slope[°]	Cool Cap[kW]	Heat Cap[kW]	Version
1	350	40	53	61	290
2	550	40	53	61	290

3	750	40	78	90	400
4	750	40	122	142	650

Table 13: Parameters of the best solution founded

Between them is not possible to define just a single solution, but further consideration can be done: for example if the main goal of the plant is to reduce the PEC used (so the amount of money for energy), the solution that provide less PEC (solution 4) should be performed; on the other hand if the plant is limited by a certain amount of capital amount of money available before the development of the project, solution 1 should be choose, because is the one with less PV area, so lower investment cost (see Fig. 21).

Table 14 report the main performance data of the chosen solutions:

Best Solution	**InEx [€]**	**Savings, yearly [€]**	**OpEx yearly [€]**	**PBT [year]**
1	1.09E+05	3.94E+04	3.76E+04	2.05
2	1.55E+05	5.88E+04	1.82E+04	3.16
3	2.12E+05	7.87E+04	-1.69E+03	4.08
4	2.24E+05	7.99E+04	-2.94E+03	5.35
	PEC [kWh]	**PEC red [%]**	**CO2emission_kg**	**CO2 red [%]**
1	2.91E+05	39%	6.91E+04	40%
2	1.85E+05	61%	4.30E+04	63%
3	8.79E+04	82%	1.91E+04	83%
4	8.56E+04	82%	1.86E+04	84%

Table 14: Performance and economic data

Is possible to see that from solution 1 to solution 4 the price of investment doubled from 110000 € to 225000 €, due to especially to the increase of the PV Area, from 350 to 750 m2. The operational cost of the solutions 3 and 4 on the other hand is negative, that means that the net amount of energy is not consumed but sold: in this case will not be sold to the grid but send to other buildings of the university. Both CO_2 and PEC reduced from 40% to 83% respect to the initial case. The PBT goes from 2 year to 5.35, from solution 1 to 4.

3.2 Best Solutions Investigation

Will be now investigated monthly these four situations: Fig. 23 reports the electric solar factor monthly and is possible to see that even if the Solution 1 (350m2) that is the one with low PV area can perform an electrical solar factor of 50%. Solution 2 (550m2) provide better results, while the best results are provided by Solution 3 and 4 (750m2) provide always more than a solar factor of 80%, excluded the month of December and during the summer months a factor of 100% that means that the energy produced form the PV is larger than the on needed.

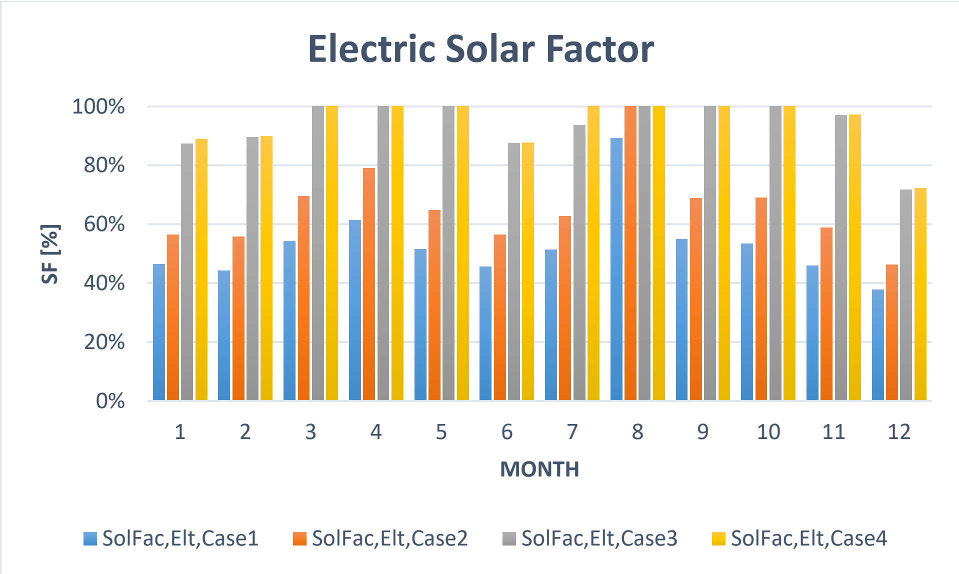

Figure 23: Electrical Solar Factor

For what concerns the thermal factor, is possible to note a peak in the month of October: this happen because the demand in this month (just in the 2nd half) is very low and the energy produced can cover partially it, even if is used a low capacity heat pump, such as in solution1.

Solution 1 gives thermal factor quite low in winter (10-20%) and doesn't produce useful effect during the summer months, so this solution should be eliminated.

Solution 2 provide better results, with an average solar factor of 15% during the whole year, but the best results are provided by Solution 3 and 4, the solution in which is provided the largest PV area.

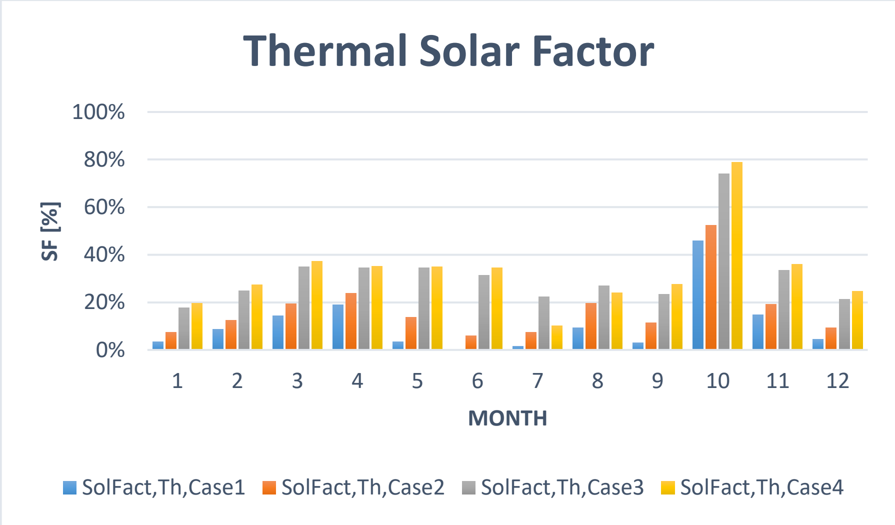

Figure 24: Thermal Solar Factor

However just one of these solutions has to be developed, so is necessary to define criteria to choose one of them.

4- CONCLUSIONS

4.1 Best Solution Preferred

Among the best solutions proposed is not possible to define one better than others but is possible to find a preferred one. The solution that is here purposed is the solution 3: this solution is defined with an investment cost of 212000 €, with a reduction of 82% of PEC and 83% of CO_2, with a savings each year of 78700€, compared to the 77000€ of the operation cost of energy of the first case: this means that with this expenditure, there will be always a positive return in terms of money, each year. The PBT of this case is four years, that means that, compared to the 15-20 years of operation of the PV plant, after the 4th year all the expenditure will be totally repaid. This solution is the one purposed because with just doubling the expenditure, respect to the solution 1, will be possible to reduce a lot the PEC consumption and CO_2 emissions, very important point nowadays for decreasing the global warming.

However, it has to be take in account that the real cost of investment can increase more during the planning, so this means that at the end the payback time may be large.

Another point that should be considered is also the money available from the university or questions related to the economic balance.

However, the project of a PV plant will be always a good investment, also for other possible solutions, considering that the payback time is just some years.

To improve more the efficiency of the system, both in terms of electricity and thermal energy, other possible solutions and modifications can be studied for this system.

Concluding, is possible to say that, even if the objective of this work is not to develop the Pv plant, but just an autonomous work done in order to have a successful methodology to study this kind of systems. Is possible to say that the objective so has been reached.

4.2 Future Works

Different possibilities can be studied for this system, such as the introduction of a battery: as seen, there are some months in which the electric solar factor is almost 100%, so this means that there is a surplus of electricity: with a battery, excess energy can be storage and used to reduce the demand in other parts of the day in which is necessary (i.e. during the night) or for increasing the electricity that can be used for the PV coupled heat pump, avoiding more and more the use of primary energy.

So, future works have to include an electric storage to perform a new multi objective analysis.

Another way that opens future developments to this project is to change the control strategy: in fact, now the idea was to cover always the electric consumption with the PV or the grid, while the thermal needs can be covered also by the thermal local grid. A possible solution that can be investigate in the next future is to change the control strategy, thinking to cover both the thermal and electric demand just using the PV and the electric local grid, so avoid totally the use of the auxiliary system.

Will be possible to investigate also the fluctuations of the price of electricity and gas, considering that the location (Spain) is subjected to the same problems of all Europe related to the security of energy: this work can give as an idea on how stable will be the solutions.

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