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Study and comparison of control and regulation systems for solar thermal plants

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Abstract

Solar thermal systems are mainly used for the application of small size in the residential market, with the purpose of producing domestic hot water and, in applications that allow, covering part of heating requirements. This technology is increasingly used in other fields of application through the adoption of largest size systems that are more complicated than residential systems and require a detailed and careful design. Among the different phases of design, there is the study of the best system of management and control; this research aims to develop a help for designers during this choice. The first step of this work has been a commercial search in order to determine the current modes of control of solar thermal systems. After, were made some dynamic simulations using some of the control mode previously defined. The simulations were done with Matlab-Simulink simulation software using a stable and calibrated dynamic model. Simulink is a graphical interface that uses different types of elements (blocks) that allow creating models to simulate a dynamic system; that is, a system that can be represented by a model of differential equations or difference where the independent variable is time. Finally, the control modes were tested in a building energy retrofit.

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Keywords: Solar Energy, Solar Plants, Management of solar plants.

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1. Solar Energy

Solar energy represent one of the most important renewable source we should use for decrease dependence by fossil fuel.

In the last few years, it assists to an inversion in the use of this energy source; in fact, solar plants are not used to satisfy only a small part of the energy demand but are designed to satisfy most of the demand, while no-renewable systems involved to a lesser extent in the event of need. One of the more important innovation is using the solar energy for cooling demand.

The solar-cooling systems for buildings, in fact, have become a viable alternative to conventional systems since, especially in recent years, the demand for electricity in summer has reached extreme peaks for the excessive use of conventional air conditioners, up to sometimes cause the blackout of the electricity grid. For these same problems, it must think also about how to satisfy the future energy needs of developing countries [1]. The use of solar energy to produce cold becomes winning opportunity, as demonstrated by numerous pilot projects in different European countries [2,3, et other]. The use of solar energy for buildings' cooling demand is an attractive hypothesis, because the period that register the greatest demand for air-conditioning overlaps with the months during which the solar radiation is at its maximum and the days are longer. The air-conditioning systems to solar energy have also the undoubted advantage of using harmless working fluids, such as water or saline solutions. They are environmentally friendly, based on the criteria of efficiency and can be used alone or integrated with traditional air conditioning systems, to improve the air quality in all types of buildings.

Another innovative use of solar energy are SDH plants (Solar District Heating). SDH are plants of high dimension that seek to satisfy the total heat requirement for DHW in summer with solar fractions considerable also in the rest of the year. The major examples are in Northern Europe and in Germany [4] where many studies have shown the convenience of solar thermal plants respect other renewable sources (Fig.1).

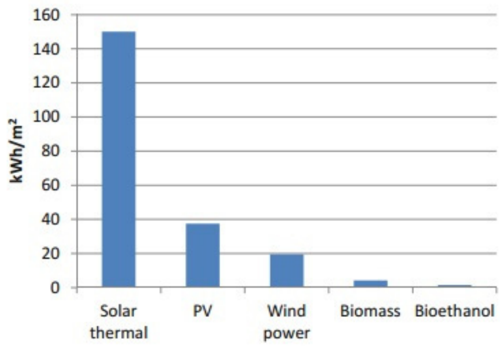


Fig. 1 Annual yield per m² of land used for different renewable energies in Northem Europe [5]

2. Control for solar plants

The controllers used in solar thermal systems are proposed generally in many different shapes and sizes and offer a variety of different options. The most basic controllers just have a differential control, which activates the solar pump when the temperature misured by the sensor on the collector is higher than the temperature of the sensor in the storage tank.

However, with innovations in the fields of pumps and regulation managements is possible to improve the production of the solar system. The aim of this work is to try to quantify this improvement and the resulting increase in annual performance. Obviously almost every controllers will be set up slightly in different way because each system is designed specifically for the single application. The pipe length, for example, between the collector and tank, will determine the most energy efficient setting for the switch of value of the pump if is used a basic regulation. The most important innovation is the possibility to regulate the pumps' speed by the inverter, with which the average temperature of the solar collector fluid is determined not only by the inlet temperature, the ambient temperature and the solar radiation, but also by the flow rate. The faster is the flow rate, the less is the time during which the fluid absorbs solar heat and the lower is the outlet temperature (for given weather conditions and inlet temperature). Lower outlet temperature means lower heat loss from the collectors and thereby higher collector efficiency. Investigations in the field of electricity consumption of pumps is one of the technical improvements in the solar thermal systems, the minimization of the auxiliary energy demand becomes more and more important when this plants are used for decrease the electricity demand. Hence, for an economic operation of solar systems, energy saving pumps or energy saving management are required.

To use variable speed pumps, the motor must, of course, be dimensioned for the worst conditions, that is for the maximum speed, which is equivalent to the normal working conditions reached with the engine running with electric current line used as it is delivered from the manager system. It will be the inverter that, by limiting its function reducing its number of round per minute (obtained by changing the frequency of the current) gives the machine the characteristic to modulate flow rate and pressure. Finally, the use of variable control like PWM (Pulse With Modulation) increase pump life by more than 30%.

Below the main control strategies taken as reference (Fig.3):

1. The solar pump turn on when the temperature difference between the bottom of the tank and the hottest part of the solar collector exceeds a difference of set temperature and turns off when this difference falls below a certain value (Fig.2). The pump operates at a fixed speed. Usually standard settings or switch-on temperature difference are from 5 K to 8 K. In principle, the longer the pipeline form the collector to the storage, the greater the temperature difference that should be set, while the switch-off temperature difference is normally around 3 K;

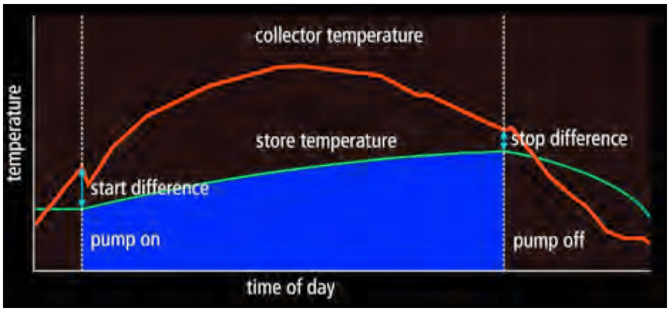


Fig. 2 Function of a temperature difference controller shown as the daily progression of the collector and storage temperature [6].

2. The solar pump have a speed control; the controller constantly measures the collector temperature and the bottom of the storage temperature and varies the pump speed accordingly. The greater the difference between the collector and the storage tank, the faster the flow through the system;
3. The pump have a speed control and regulates the flow of water to obtain the fixed temperature value at the exit of the solar collectors. The control system is also programmed to stop the pump when the temperature of the outlet water from the collector is lower than the corresponding inlet temperature or than the storage temperature; this strategy limited the heat loss because the tank always operates at the minimum temperature required by downstream equipment, and, also prevent any overheating that occurs during periods of low use of solar energy;
4. This is a variant of system for larger systems. A radiation sensor measures the solar radiation. At a threshold value of, for example, 200 W/m² the controller switches on the solar pump, and the three-way valve initially bypasses the heat exchanger. The solar circuit heats up. When the temperature difference between the solar circuit and the storage reach the set, the controller active the valve and the storage starts to charge. The minimum irradiance to start up the primary pump may vary depending on the

storage temperature. If the storage temperature is low, small irradiances may be acceptable whereas a high storage temperature means that a higher (minimum) irradiance level is required to charge the storage. This control mode allow starting the primary circuit already from the early morning when the radiation is not enough to heat the tank but allows to heat the primary circuit. This heat in the primary circuit is exploited when the three-way valve rotates or a pump of the secondary circuit starts avoiding having the initial morning heating of the entire circuit.

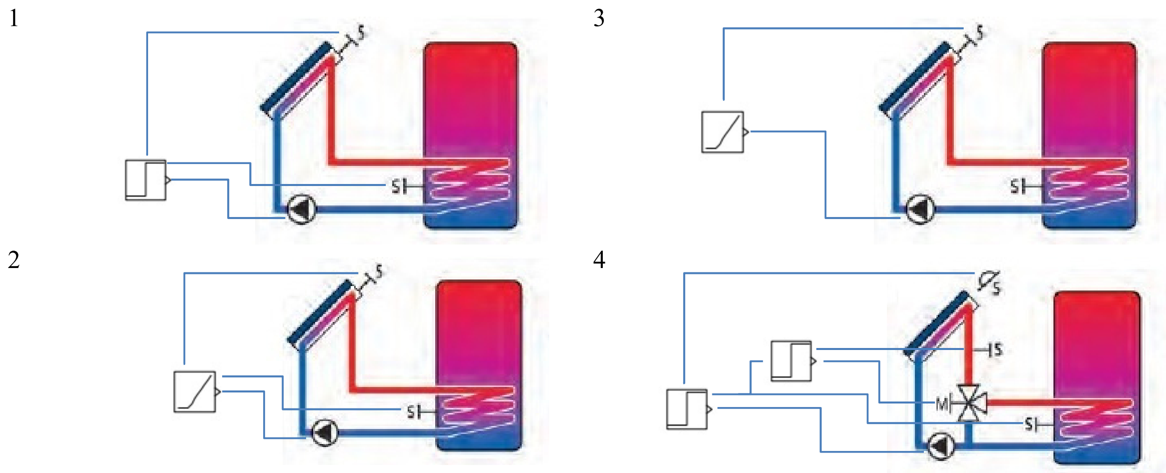


Fig. 3 Different control strategies for solar systems

Controllers have also other functions: for example, in big systems, the controller can be used to direct the solar energy to the part of the tank (or thermal storage) where it is needed most. When there is a heat requirement, the solar energy will be directed to the top of the tank and when the top of the tank is satisfied, it will be directed to the bottom of the tank. Functions as these are not considerate in this work.

Controllers also give useful information about the system. The standard controllers display the current status of the system including the temperature of the collector and at the bottom and top of the tank, so you can see how much hot water is available. It also displays the pump speed percentage and a cumulative count of the pump operation hours. Controllers can also be used for heat quantity measurement. This allows you to measure how much energy has been harvested by the system and, with additional sensors, to calculate how much energy has been inputted to the storage.

3. Simulation

The simulations involved two types of systems:

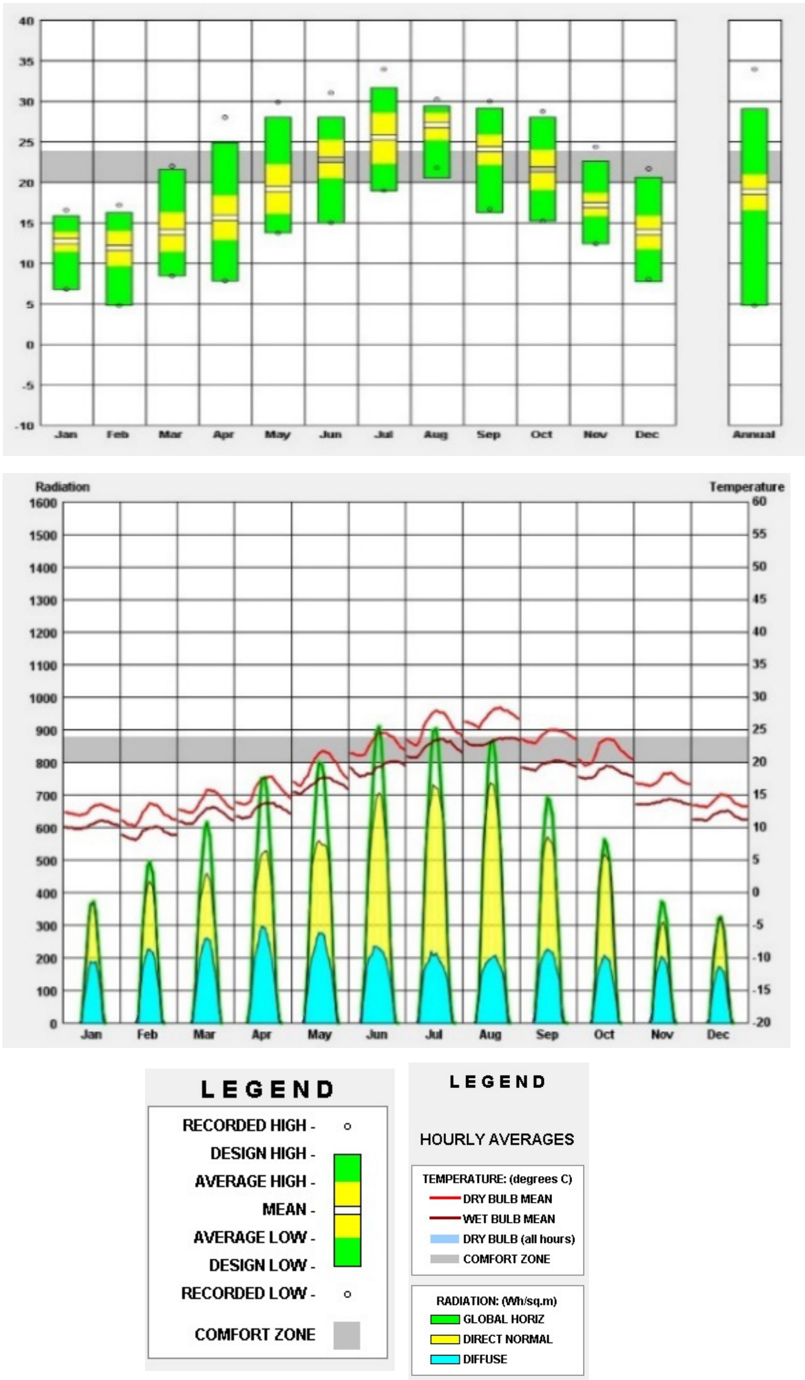
- Plant A : Solar plant of medium size (170 m²) used in a solar cooling system for room air-conditioning;
- Plant B : Solar plant of large size (980 m²) built in a district heating network to cover the summer demand due to the consumption of domestic hot water (Solar District Heating).

Both of plant was simulated in two different place, a Mediterranean (the first one) and a middle/north Europe clime in the summer time (from May 15th to September 15th). Simulations have a time step of 15 minute, while weather data are hourly.

Below are showed the weather data considered for simulations (Table 1) and the main technical data about plants (Table 2):

Table 1. Weather data (outside temperature and solar radiation) considered for simulations [7]

PALERMO 38.18° , North 13.1° East



COPENHAGEN 55.63°C North, 12.67 East

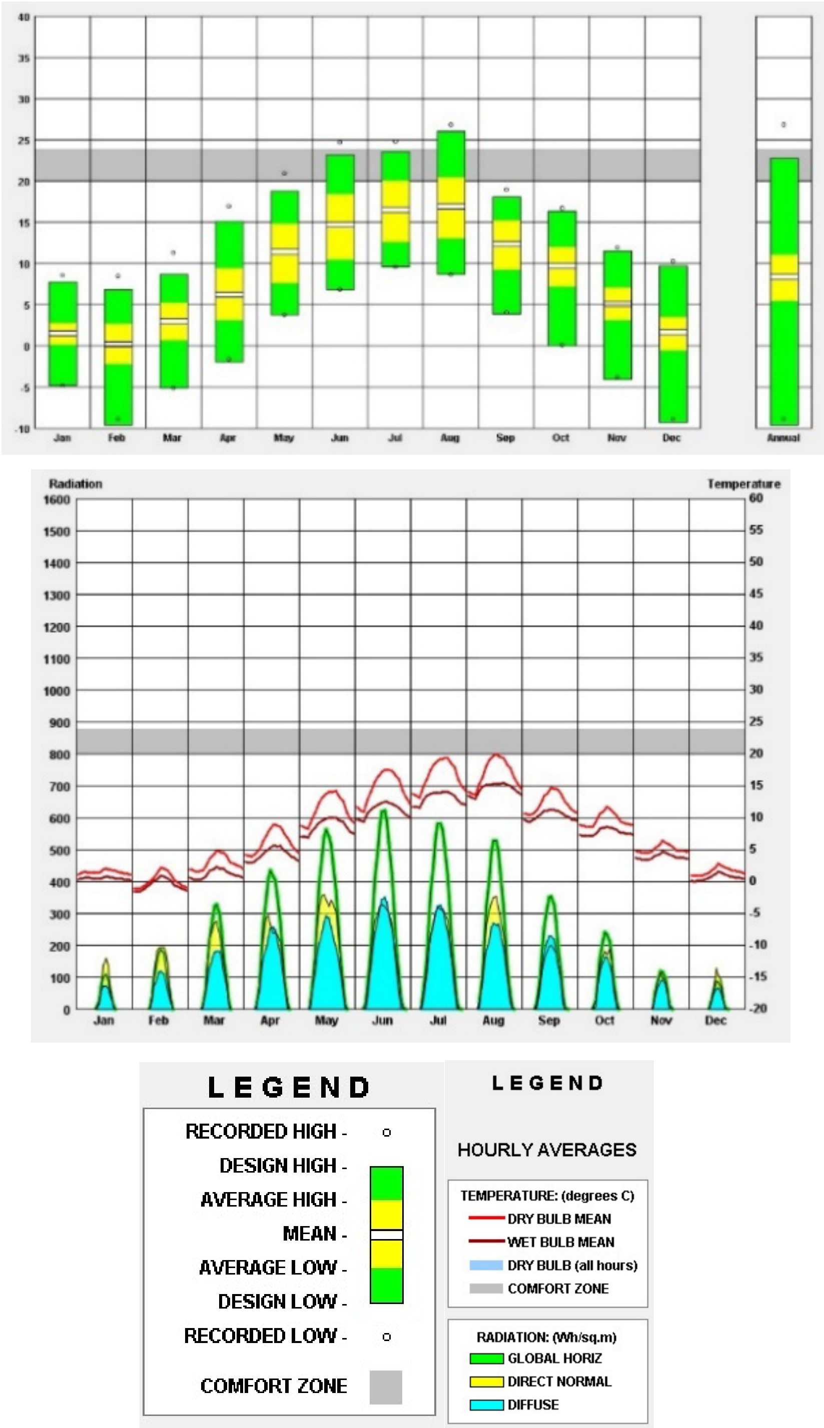


Table 2. Technical data about plants

	Solar area [m²]	Inclination	Circulator power [kW]	Nominal flow rate [m³/h]	Storage [m³]
Plant A, PALERMO	170	30°	0.3	10.2	4.5
Plant A, COPENHAGEN	170	45°	0.3	10.2	4.5
Plant B, PALERMO	980	30°	4	58.8	50
Plant B, COPENHAGEN	980	45°	4	58.8	50

4. Solar heating and cooling plant in a building's energy retrofit

The same regulation modes tested in previous simulations were used to determinate the productivity of solar heating and cooling plant in a total glass building. The building is in Palermo and it has been energetically retrofitted according to new European standards about nZEB [8].

The building consists of two floor above ground and has a volume of approximately 3000 m³, the rooms are used for offices, conference rooms and other business activities. Before the retrofit, energy demand was about 10 kWh/m² year for heating and 102 kWh/m² year for cooling (by simulation with Energy Plus). The energy retrofit has resulted in:

- Reduction of the transparent surface with opaque elements;
- Replacing windows with higher performance elements;
- Adoption of solar shading systems;
- Creating a green roof to reduce the cooling demand [9];
- Installation of a solar plant on vertical wall (south facade) for a solar and heating system (Fig.4).

With these interventions, the energy demands decrease at 2 kWh/m² year for heating and 18 kWh/m² year for cooling (Fig.5).

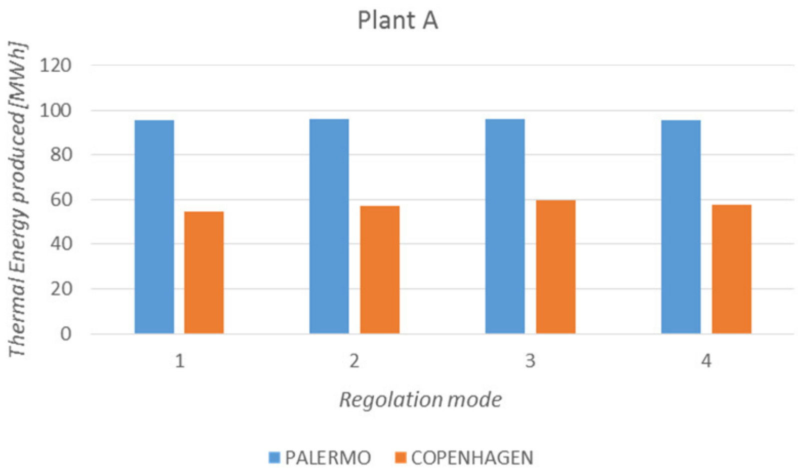
Fig. 4 Example of evacuated solar collector installation in building facade

5. Results

The simulations considered both of plants in both of places; below are shown the results. Thermal energy indicates the energy captured by the solar system and transferred to the storage system while electric energy indicates consumption of solar pumps.

Table 3. Results of simulations

Control strategy	Plant	Energy [kWh]	PALERMO	COPENHAGEN
Control strategy 1	Plant A	Thermal Energy	95600	54550
		Electric Energy	356	287
	Plant B	Thermal Energy	147721	111050
		Electric Energy	6260	5499
Control strategy 2	Plant A	Thermal Energy	96010	57336
		Electric Energy	332	261
	Plant B	Thermal Energy	147963	111266
		Electric Energy	5875	4891
Control strategy 3	Plant A	Thermal Energy	96020	59498
		Electric Energy	330	236
	Plant B	Thermal Energy	147731	111386
		Electric Energy	5117	3777
Control strategy 4	Plant A	Thermal Energy	95702	57405
		Electric Energy	343	306
	Plant B	Thermal Energy	147657	111304
		Electric Energy	4943	4115



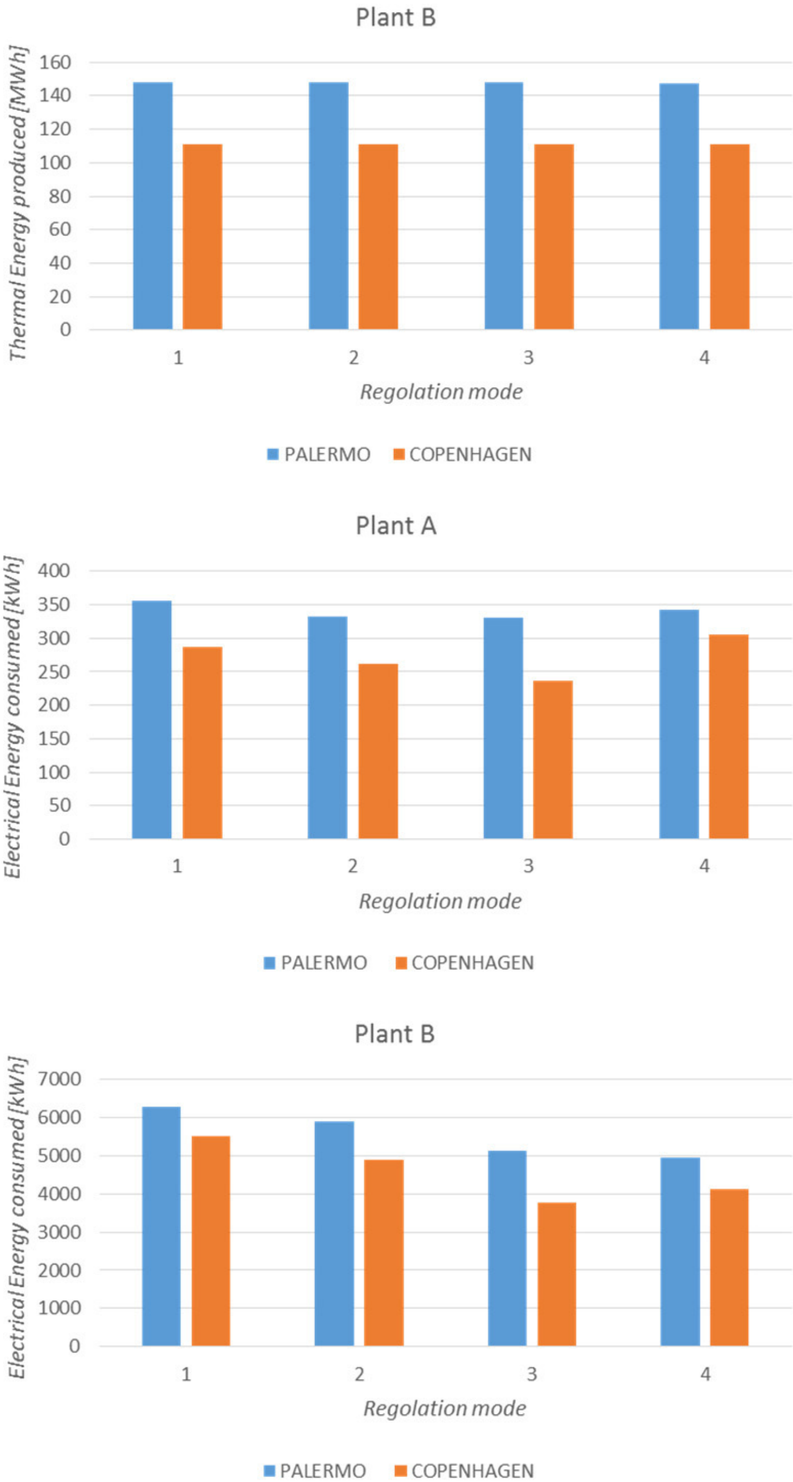


Fig. 5 Results of simulations

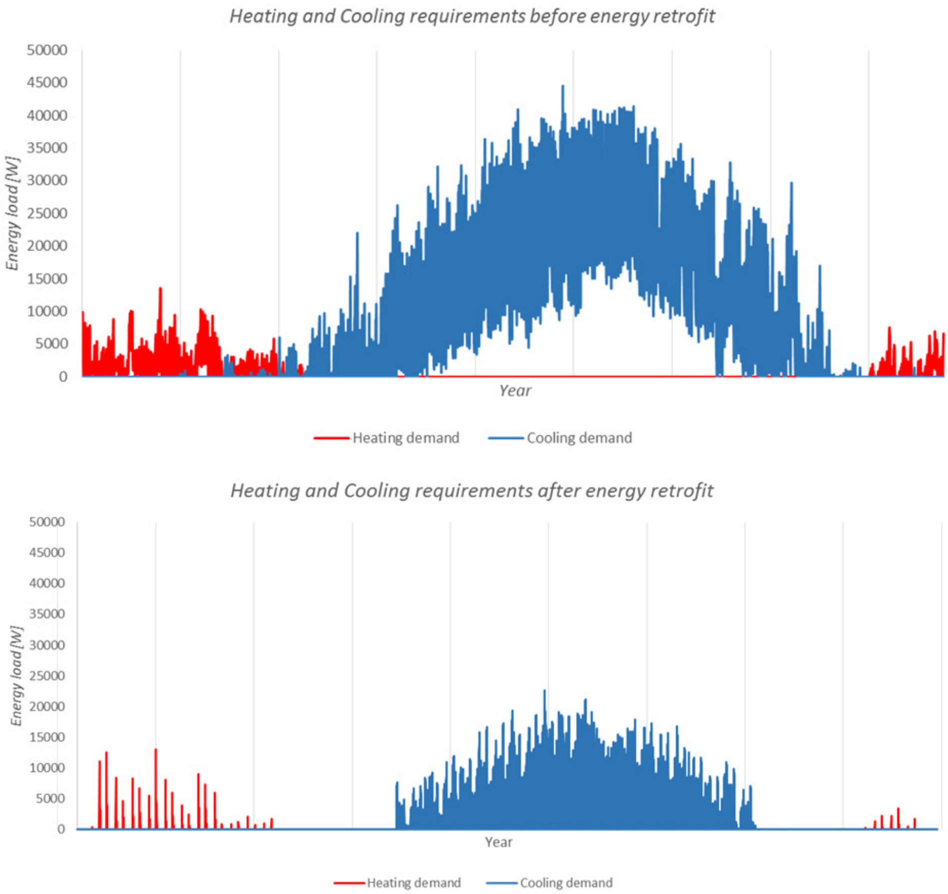


Fig. 6 Energy requirements before and after energy retrofit

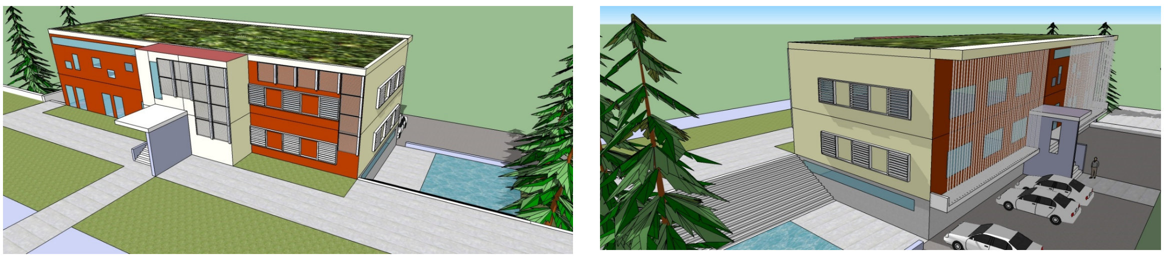


Fig. 7 Rendering of building after energy retrofit

Table 4. Energetic saving in the SHC plant installed in a nZEB

	Electric Energy [kW]	Percentage variation
Control strategy 1	542	0 %
Control strategy 2	507	-6.4 %
Control strategy 3	486	-10.3 %
Control strategy 4	613	+11.4%

6. Conclusion

The first part of this study has the aim to test the performance of different control modes applied to the pumps of large solar plants. The results show that for the same heat energy transferred to the storages there are some regulation modes that induce a lower electrical consumption. For the Plant A (170 m² in a Solar Heating and Cooling plant) the most efficiently regulation mode is number 3 with an electric energy decrease of 7.3% for Palermo and 17.8% for Copenhagen respect to mode 1, choose as reference. For the plant B (980 m² in Solar District Heating) the most efficiently regulation mode is number 4 with a decrease of 21.1% for Palermo and 25.2 % for Copenhagen. The results show that is more convenient to use these control technologies in large size plants and in sites with low solar availability.

In the second part of this work, the different regulation modes were tested in a solar heating and cooling plant installed in a building deeply retrofitted. The plant is composed by 55 m² of solar collector with evacuated tube, two tanks (one for hot water and the second for cold water) and an absorption chiller. The results demonstrate firstly that in this type of buildings the only use of renewable energy is enough to cover the energy demands and secondly that the electric energy savings achieved by using the regulation modes proposed are economically convenient [Table 4].

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