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Study Case of Solar Thermal and Photovoltaic Heat Pump System for Different Weather Conditions

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Abstract

The combination of solar thermal and photovoltaic technologies with the new heat pump systems is a welcome advancement. These systems could have similar efficiency all the year at different locations if we adjust the solar storage temperature according to the weather conditions. Solar heating with a heat pump system for buildings has been designed to achieve different values of the fraction of primary energy saving using the Flat Plate Collectors (FPC) and solar photovoltaic (PV) technology, and having the higher efficiency of the system with net zero energy in thermal production. New systems will need to accomplish the new Directive 2010/31 / EU, which sets that by 31st December 2020 new buildings in the EU will have to consume 'nearly zero-energy' .

Solar Thermal, Heat Pump, Photovoltaic, net metering, combisystems

1. Introduction

The highlights from the Task 44 in 2012, proposed that solar heat can help enhance the performance of the heat pump by raising the evaporation temperature, the solar heat can be stored at low temperature (0-20ºC) thus making good use of the collectors even during the cold days. Solar PV can also help to reduce the used power.

This study case analyzes two configurations of solar systems with a new water-to-water heat pump, in different countries for thermal uses; one for Domestic Hot Water (DHW) and another for Heating and DHW use, these are the most common thermal necessities for domestic applications (Hadorn 2010). The resulting thermal energy costs obtained for FPC are from 2 to 14 c€/kWh depending on the collector type applied and the working temperature (Vives et alt. 2013). The PV has been a very interesting way to produce electricity and thermal energy if we combine this with heat pump (vapor compression cycle). About 50% of southern countries' electricity comes from lignite power plants with an electricity production cost of 0.04 €/kWh, with high CO_2 emissions. However the final price for households has doubled, from 0.07 €/kWh at 2001 to 0.15 €/kWh in 2013 (Eurostat 2013), and the PV cost is 0.07-0.12 €/kWh. Counting that a modern compression machine has a 3-5 Coefficient of Performances (COP), the actual cost of thermal production with Heat Pump is 0.05-0.03 €/kWh, depending of the working temperatures (Gordon 2000). Recently, reductions in electric PV costs and mature technology of air-to-water and water-to-water heat pump have provided a new model: solar-electric assisted heat pump. This system comes with fewer drawbacks than solar thermal energy, a smaller price tag for residential applications. Nevertheless, the best system will be a combination of both. The development of modern net zero-energy buildings (NZEB) became possible not only through the progress made in new renewable energy and construction technologies and techniques, but it has also been significantly improved by the combination of all the techniques and advanced combisystems.

2. Description of the system

The auxiliary energy is coming from a Heat Pump (water-to-water system with inverter control) usually used

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for geothermal applications, that can work with electricity from the grid or the PV system. A high efficiency Heat Pump in the range of 5 to 20 kW has been used to cover the energy needs of households with low energy demand occupied all the year.

Simulating the whole year system we reach different solar fractions depending on the efficiency of the system, the working temperature of the storage system, and the different COP of the heat pump. This system can operate with outside temperatures lower than 0ºC, a high solar fraction and with a high efficiency of the solar collector. The storage operating temperature has to change during the year according to the external temperature and the solar radiation, in order to obtain a higher efficiency from the collector, and to work with the maximum efficiency of the heat pump. Only in summer or spring can be the solar energy used directly for thermal production. The FPC works in serial with the heat pump during the cold season and parallel during the spring and summer. Finally we will use the cooling of the evaporator to increase the PV efficiency at southern countries. This system can have a very high Performance coefficient and adapt its efficiency for whichever conditions. It is ideal for both cold and mild climates.

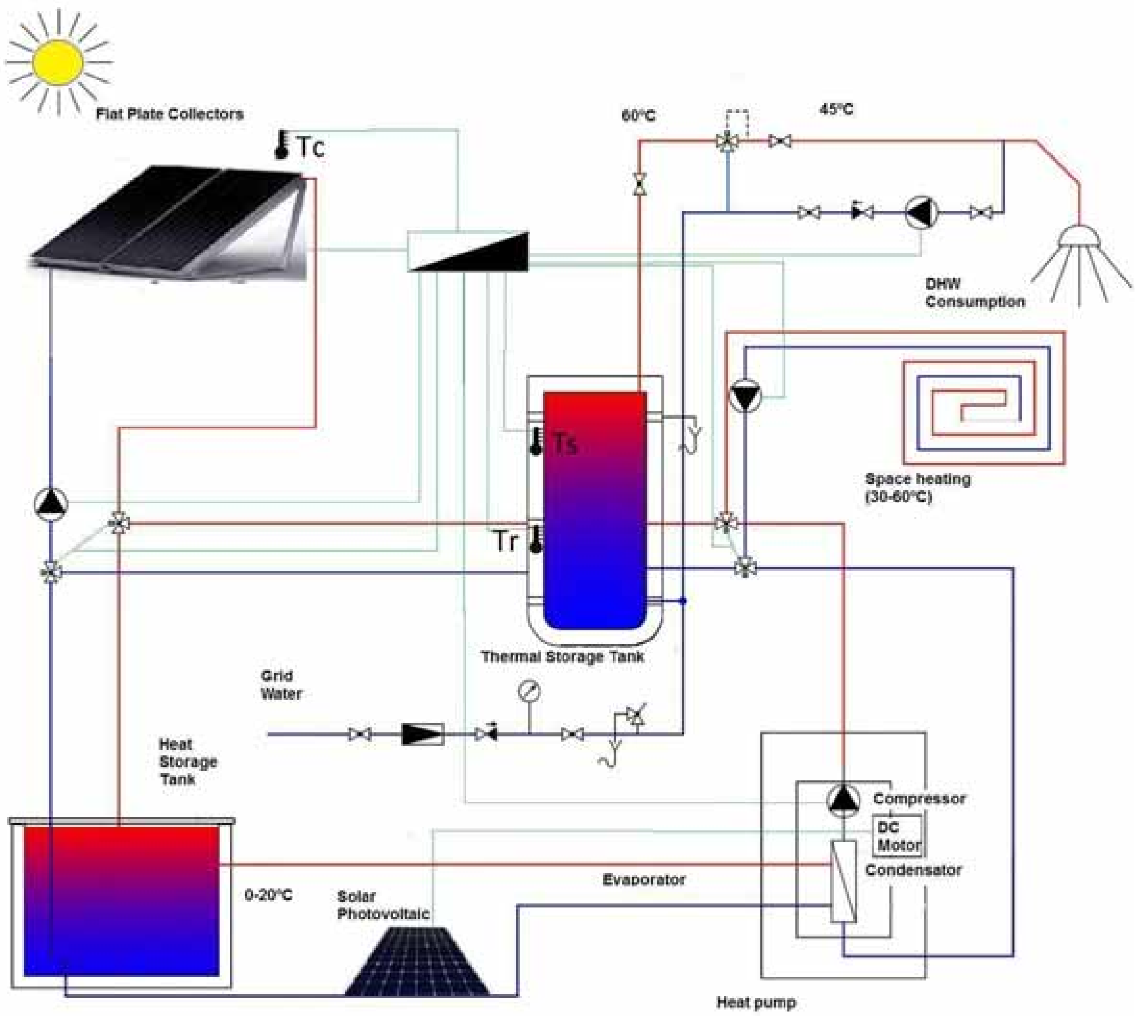

Fig. 1: Figure of the Solar Thermal and PV Heat Pump system for DHW and Space Heating

The typical configuration of the solar thermal systems is with a fixed working temperature, close to 60ºC. Nevertheless, in the task 44 a lot of cases have been studied with the Heat pump working temperature lower than 60ºC, due to the fact that this high efficiency system can supply the rest of the energy with electricity. Most of the geothermal heat pumps are working with a maximum temperature of 20ºC in the evaporator, and they can arrive to 60ºC in the condensator to cover all the thermal necessities. In the Mediterranean countries the air-to-air or air-to-water heat pumps usually have a good efficiency; there are only a few days and hours with temperatures below 0ºC. On the opposite, at the northern countries there are some months with a lot of hours below 0ºC and that´s when they use more geothermal. In the case of the Mediterranean countries it would be cheaper to use a big surface of unglazed collectors (Moià et Alt 2012) against the glazed collectors.

However, at this study in order to be able to compare properly all the systems we have used the same technology for all the locations, glazed collectors with a high efficiency, specially designed for extreme conditions and the same water-to-water heat pump (Geothermal Units). The simulated heat pump has a maximum heating power of 13 kW and a nominal COP of 3,56 for heating temperatures of 35ºC-45ºC, and evaporating from -5ºC to 10ºC, with a refrigerant R-410A.

The Photovoltaic system has been a standard one, the panels with polycrystalline silicon between 260-330 Wp, and the inverter with a nominal efficiency of 95,5%, with a 95% of cleanliness and 2% of losses in the cables.

3. Simulation and Results

We have used different simulation programs for comparing and simulating different parts of the system: for the demand LIDER-CALENER (Spanish software for TBC energy performance certificate of the building base in DOE2 simulating system), for the solar generation POLYSUN, TRNSYS and GREENIUS. Most of these programs can be used to simulate different Collectors technologies; the user can compare each system creating the collector file at the same site but usually with a fixed working temperature. In all the locations the typical meteorological year (TMY) has been taken in mind. In this first study, we haven't considered any electrical storage or batteries; a Net metering contract with the electrical company for the electric production of the PV system has been supposed in all the locations to compensate the excess of summer with the low winter production.

ST Collector Efficiency $\eta = 0{,}807 - 3{,}075(T_m-T_a)/G - 0{,}022((T_m-T_a)/G)^2$ (eq. 1)

Unitary Energy Consumption Heat Pump $kWe = 1{,}20122-0{,}0400633T+0{,}0010877T^2$ (eq. 2)

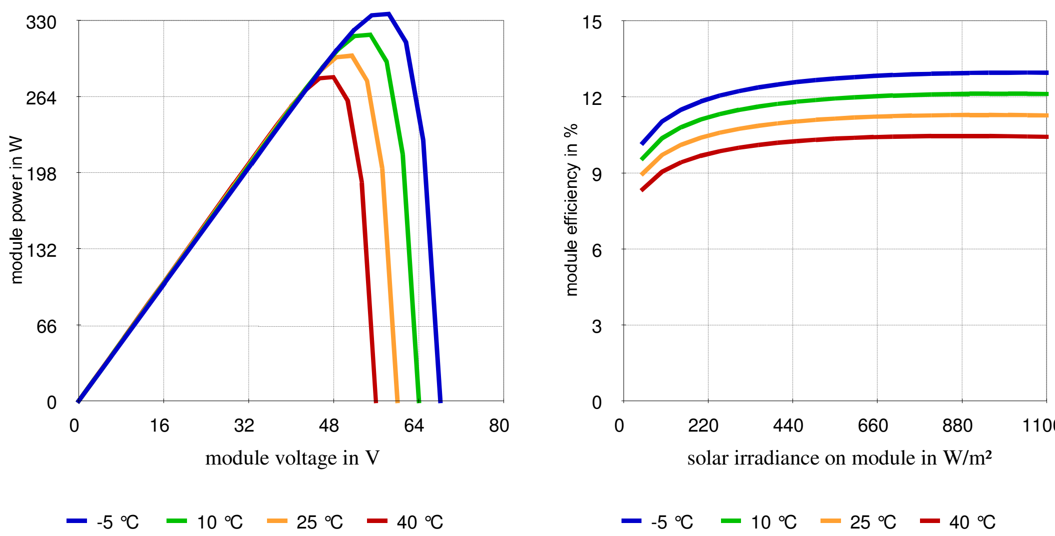

Fig. 2: Figure of the PV efficiency and power according to the Voltage, irradiance and temperature(ºC). [6]

Tab. 1: Results of one year simulation in three locations for DHW.

Location	Thermal Energy Demand (kWh)	Max. Solar Energy kWh m^{-2}	Electric Energy kWhe	Solar Thermal Fraction	Average FPC Efficiency	Solar Surf. m^2	Min.Power of the PV (Wp)
Greece	4426	1131	548	72%	73%	3	428
Spain	4695	1169	547	70%	73%	3	440
Germany	5619	688	596	74%	71%	6	780

For the two considered models above mentioned, the solar thermal energy has priority in front of other renewable energy sources, and reduces the overheating in the solar panels.

The first one, hot water demand for a medium household occupied by 8 people during a year for three different locations, Athens, Berlin and Mallorca. Solar collectors production ratio (kWh m^{-2}·year) was based on collector aperture surface and is presented in Table 1.

The second model has been estimated for four locations, consisting of a constant hot water demand for 4 people during a year. The typical residence considered is an apartment of 100 m² floor area, with an 80 m^2 of heating space. The residence is modeled into two zones: a conditioned zone representing a 50% of the total floor area during the day and another conditioned zone during the night. It has been supposed that it's a good quality house, according to sustainability criteria (insulation, orientation,..). When we are using renewable energies we need a low demand to make the system cheaper. For each location has been supposed a different thickness of insulation, using EU criteria for Athens, Berlin and Palma de Mallorca (Spanish Technical Building Code (TBC), that obliges the installation of thicker insulation in colder places, and less insulation in warmer places. For Moscow it has been considered the Russian law 2003 for the insulation (according to Building regulations and rules 23-02-2003).

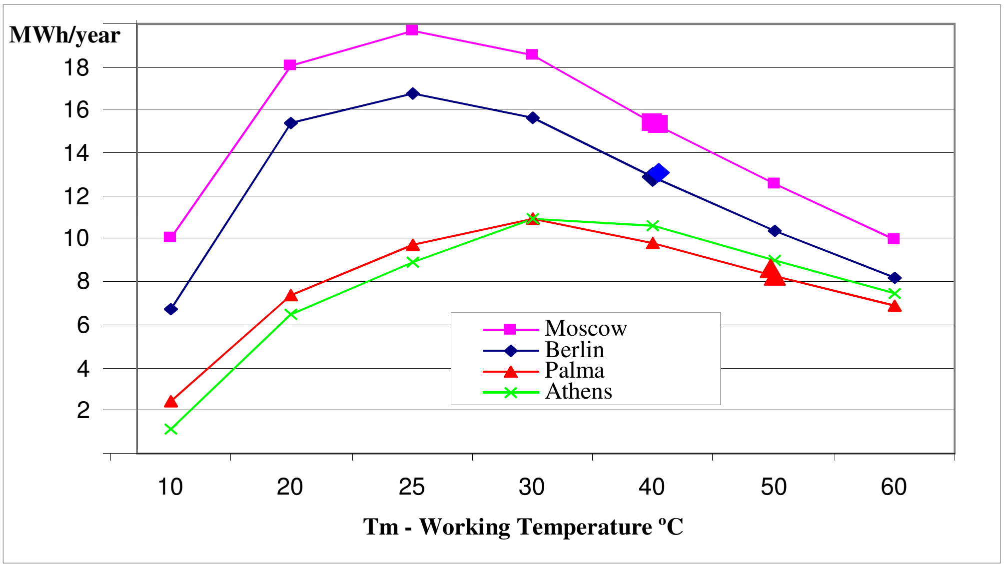

Fig. 3: Figure of the Solar energy with constant solar working temperature(ºC) for the four locations with GREENIUS

In figure 3 it becomes evident that for each location we can have the annual maximum solar energy with the medium temperature of the solar collector between 25 and 30ºC. For temperatures lower than 25ºC the efficiency of the FPC is higher but the energy requirements are lower and, therefore there are many hours with excess energy for a given storage volume. Each location has a different surface, according to the annual thermal necessities as to achieve a similar solar fraction.

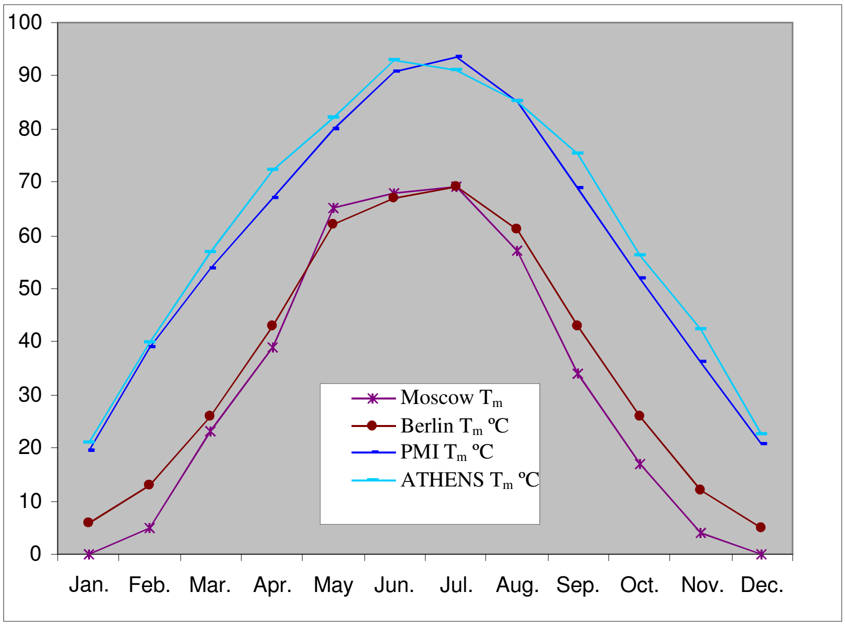

Fig. 4: Figure of the estimated solar working temperature (ºC) for the four locations during a typical year

When the outside temperatures are rising the thermal demand is reducing, and during several months there is enough energy to cover the thermal demand so it's not necessary to work at the maximum efficiency point. We can work at higher temperatures to avoid overheating and stagnation problems. This system can be only solar thermal between 40 to 60ºC. In order to avoid having a low average efficiency we should look for the optimal point of solar panels so as to accomplish the maximum solar energy gains without overheating. The medium temperature will be usually in winter lower than 20 ºC and in spring and autumn lower than 50ºC, in summer the FPC are working with more than 60 ºC. When the medium temperature of the collectors would be higher than 45ºC we will make a direct heat transfer to the DHW or heating system, in parallel with the heat pump. The high temperatures that can occur may require special design to prevent overheating, especially in the Mediterranean countries.

According to the efficiency of the PV and the FPC, in this scenario we propose a control system, adapting the working temperatures of the solar primary circuits for whichever conditions, and spend more energy during the periods with low solar radiation. Nevertheless, we can guarantee always a comfort temperature for space heating and DHW. From figure 4 we can see the proposed working temperatures for each location and each month. The control has to be a dynamic system with an algorithm that has to change the point according to the energy demand, solar radiation and external temperatures. The control system will have to adapt its algorithm to smart systems, connected to a prediction weather server in order to archive the maximum solar fraction, and adapt the working temperature at the optimal point. This system needs an advanced simulation system and its design has to be improved and adjusted for each location according to curve demand and technology.

3.1. Moscow. Russia

Located at Latitude 55,75ºN 37,62ºE, with a minimum temperature of -24,4ºC, maximum of 30,0ºC, and a mean temperature of 5 ºC. The annual sum of global irradiation GHI is 961 kWh m^{-2}. Moscow is one of the coldest world capitals in winter, with very low solar radiation. Actually the energy prices in Russia are quite low, but in a few years it's foreseen to be similar to the EU countries. 90% of the Russian mix energy system comes from fossil fuel. Only a small amount is produced from hydropower plants and other Renewable Energies Sources used for power production are almost non-existent which makes Russian economy more vulnerable to a collapse in oil prices than other European countries. Solar energy production is very low in Russia and there are very few solar thermal and photovoltaic systems despite the country's large potential and higher economical increase than the EU. The country has similar solar radiation to Germany but solar thermal is still a very small market. Russia presents interesting market opportunities for EU renewable energy equipment companies. Russia has a bigger potential from 43º to 60º, and less potential at the latitudes

60º to 80º, due to the very low temperatures and low radiation at winter. Even the Geothermal heat pump systems have only just begun to penetrate the Russian market on the contrary to countries with similar weather conditions (Sweden, Denmark, Germany,..). Until now there the conventional sources where most known. The maximum values of COP are 4.24 in the south regions of Russia, and the minimum values of, correspondingly, 2.73 on the north.(Vassiliev and Gornov 2010).

There is some successful experience in Solar-Heated House, with low demand in extreme conditions, a closer example will be at Vladivostok (Latitude 43º) with a surface of 15 m^2 of Solar collectors, and storage tank of 750 liters, with a 23% of solar fraction and using solar passive energy they arrive to the 38% (Kazantsev 2011).

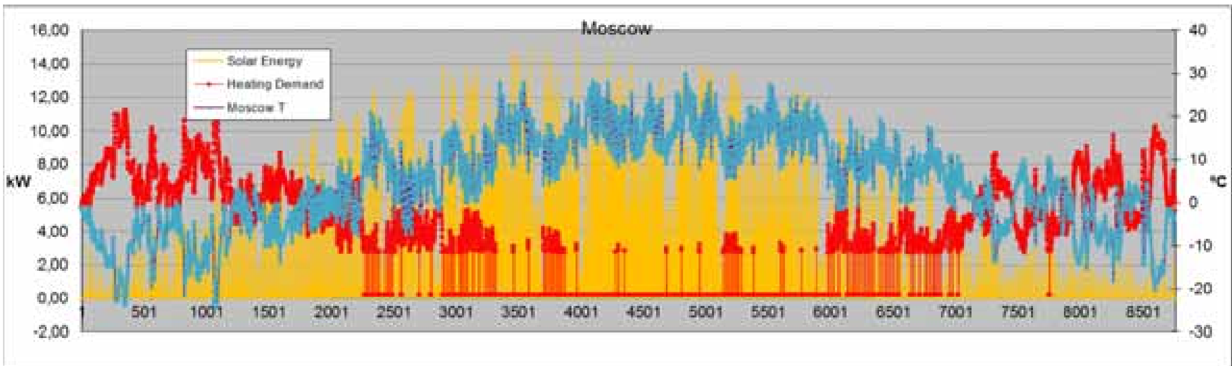

Fig. 5: Figure of the ambient temperature, thermal necessities and solar power during a TMY in Moscow

In Moscow with a first simulation, in a standard house of 100 m^2, it´s necessary a surface of 30 m^2 of solar thermal collectors and a storage tank of 3 m^3 for the combisystems and a simulated thermal necessity of 112 $kWh\cdot m^{-2}$ year with a peak heating demand of 11,3 kW. For a normal polycrystalline PV we will need an approximate surface of 22 m^2 . The total of 52m^2 of surface for the PV and ST system can arrive to zero emissions so as to cover the thermal necessities. For this location it will be necessary a big surface to arrive to a net zero emissions building, and cover all the thermal necessities. Other models will be studied with seasonal storage or standard geothermal technologies, in order to reduce the solar surface, and the initial investment of the system.

Simulating another house with a good control system, higher insulation and lower heating temperature system (Fancoils or floor heating 25-45ºC) we can reduce the energy demand a 50% and optimize the size of the system. At Continental climates with latitudes lower 55º, it gives us bigger systems than the conclusions of the Task 44, with 12 m^2 and storage of minimum of 1 m^3. In Russia with this model the surface would be 18-20 m^2 with a storage minimum of 1,25 m^3.

3.2. Berlin. Germany

Located at 52,47ºN 13,30ºE, with a minimum temperature of -14,6ºC, maximum of 31,4ºC, and a mean temperature of 8,9 ºC. The annual sum of global irradiation GHI is 993 kWh m^{-2}. In Berlin, which has a hard winter, the combisystems are quite common – they have a share of 65% of the market- with a solar surface 8 to 15 m^2 and buffer storage 500 to 1000 litter. Germany´s installed capacity is the largest in the EU, and the last years since 2009 (ESTIF) has increased the surface of installed collectors due to the obligation to cover a percentage of the thermal needs.

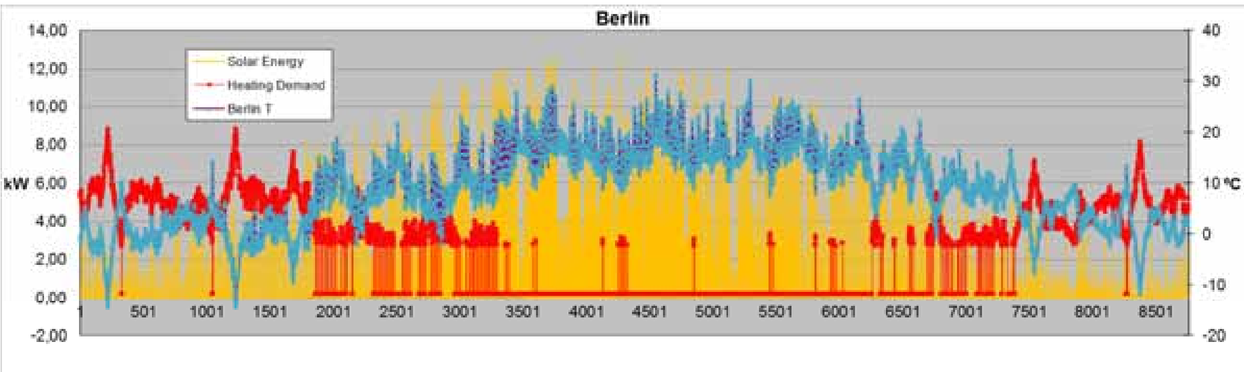

Fig. 6: Figure of the ambient temperature, thermal necessities and solar power during a TMY in Berlin

For Berlin we would need a surface of 24 m^2 of solar collectors and storage tank of 2,4 m^3 for the combisystems. It has been estimated with a simulated thermal necessity of 79 $kWh \cdot m^{-2}$ year, with 9 kW of peak heating demand. Installing an approximate surface of 14 m^2 PV panels, the total surface that we will need will be 38 m^2 of PV and ST system so we can arrive to zero emissions to cover the thermal necessities. We will need almost 50% of the heating surface to cover the 100% of the thermal demand with renewable energies.

The cost of this system could be more than 10.000 €, but if we take in account than the apartment prices in Germany's capital, are around 2.596 € per square meter [10], this is less than a 4% of the total buying cost. Besides, if we consider that energy prices in Germany are very high, the payback of the inversion will be less than 10 years.

3.3. Palma de Mallorca. Spain

Located at 39,33ºN 2,39ºE, with a minimum temperature of -6,2ºC, maximum of 40,3ºC, and a mean temperature of 16,1 ºC. The annual sum of global irradiation GHI is 1619 kWh m^{-2}. It's one of the most touristic Islands in Europe and receives more than 10 million of tourist every year. It has the same latitude of the capital, Madrid, but higher temperatures at winter. Since 2006 it's obligated to install solar energy for cover at least the 50% of the DHW necessities which has made the market grow very quickly. The most common installed systems are systems with a surface of collectors 2-4 m^2 with a 150-300 litters tank. Combisystems are very rare in Mallorca. In the proposed model, for this location, a surface of 9 m^2 of solar collectors and storage tank of 0,9 m^3 for the combisystem was estimated, with a simulated thermal necessity of 53 $kWh \cdot m^{-2}$ year and a peak of 7 kW.

The auxiliary electricity will be covered with 3 m^2 of PV. The total surface needed is 12 m^2 of PV and ST system in order to arrive to zero emissions to cover the thermal necessities. This location needs less than 12% of the surface, with a reasonable storage. Some overheating will be produced from April to September. These systems for southern locations can be used in flat, houses or other kind of buildings with a south oriented façade. The cooling necessities for this location haven't been analyzed but most of the heat pumps can be used as well to cover the cooling demand. If this were the case we would need more PV surface and air-to-water heat pump systems.

For this location an Air Source and Ground Source Hybrid system (air-to-water combined with water-to-water) could be studied as well, where the system can use the most efficient source according to climate conditions. In this case we can reduce the solar surface and the solar storage or seasonal storage, but we will need more PV surface to cover the thermal demand with the heat pump.

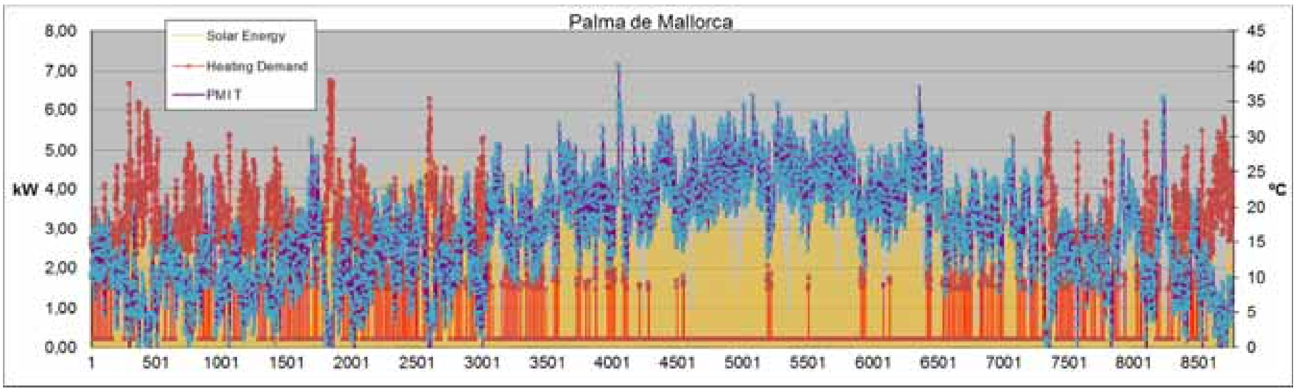

Fig. 7: Figure of the ambient temperature, thermal necessities and solar power during a TMY in Mallorca

If we take in account that energy prices in Spain are very high, especially electricity, the payback of these systems will be less than 8 years.

3.4. Athens. Greece

Athens is located at 38ºN 23,73ºE, with a minimum temperature of 0,5ºC, maximum of 38,3ºC, and a mean temperature of 18,6 ºC. It's one of the hottest European capitals with a high solar radiation. The annual sum of Global Horizontal Irradiation is 1748 kWh/m^2 and the DNI is 1856 kWh m^{-2}. Greece has the second largest installed capacity in the EU (ESTIF). The most common system in Athens is a thermosyphon system with a surface of 2-4 m^2 for DHW. Similar to Spain, the combisystems are not common in the market.

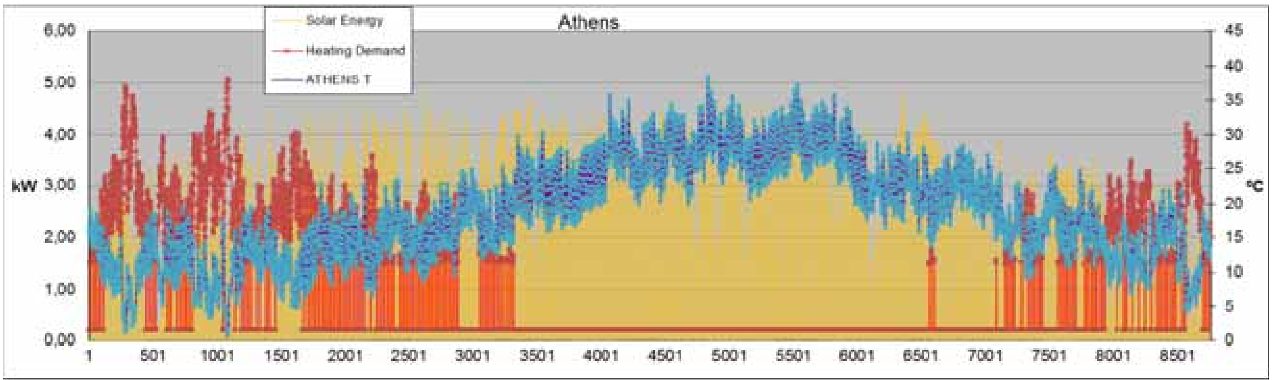

Fig. 8: : Figure of the ambient temperature, thermal necessities and solar power during a TMY in Athens

In Athens a surface of 9 m^2 of solar collectors and a storage tank of 0,9 m^3 for the combisystem was estimated with a simulated thermal necessity of 57 kWh·m^{-2} year with a peak heating demand of 5 kW. Installing an approximate surface of 3 m^2 of a PV we could cover the electric consumption of the system. The total surface of the solar thermal and photovoltaic system will be 12 m^2 in order to achieve a zero emissions in the thermal necessities. For this location seasonal storage or other technologies could be studied like an Air Source or Ground Source Hybrid system, in order to improve the system and reduce the thermal storage and overheating, produced from March to October.

3.5. Resume of the results.

Comparing all the locations we could arrive to a similar efficiency of the solar thermal panels, with high renewable thermal fraction (heat pump + solar thermal), combined with PV, this can be a solution for supplying the 100% of the thermal necessities. Increasing the PV system we could cover the rest of the energy necessities of the household. The heat pump manufacturers have made a big effort during the last years in order to arrive to high efficiency systems, and the market of geothermal systems has incremented. The Heat Pump with solar panels working in low temperatures could open a big market in locations with low radiation; even if they have cheap energy prices, like Russia.

Tab. 2: Results of one year simulation in four locations for DHW and Heating demand.

Location	Thermal Energy Demand (kWh)	Max. Solar Energy kWh m^{-2}	Electric Energy kWhe	Renewable Thermal Fraction	Average FPC Efficiency	Solar Thermal Surf. (m^2)	Power of the PV (Wp)
Athens	4530	974	354	92%	60%	9	270
PMI	4198	885	271	94%	59%	9	230
Berlin	6295	539	1812	71%	60%	24	1800
Moscow	8892	509	2388	73%	58%	30	3240

At latitudes lower than 40º, with higher solar radiation, other systems could be used, like air-to-water heat pumps, or unglazed collectors, they could make cheaper the system, but the results and prices of this study are quite reasonable. At latitude higher than 50ºC, other systems could be studied with Evacuated Tube Collectors, and arrive to other results. Other scenarios with seasonal storage or analyzing cooling demand will have to be studied in order to improve the system.

Actually in the market there are air-to-air heat pumps with PV, there are good geothermal heat pumps, and combisystems with air-to-water systems, but not yet a combination of all of them. The proposed system will need more detailed analysis for each location, and we will need to develop new algorithm and programs to simulate and test this new system. The economic results will change every year according to the prices of the devices and the energy cost. Real test will be needed, it's planned to build two test sites in Dubna University (Moscow Region) and Balearic Islands University at Palma, Majorca, in order to improve the system and demonstrate the real efficiency of all the system. There are some parameters to be improved and analyzed, like Phase Change Materials for storage, more energy or new heat pumps systems. Another parameter which can be a barrier for this system is the available surface, in order to have a proportionately sized system to the available m^2. When we are working to NZEB we will need a big surface for the solar thermal and photovoltaic panels that some constructions, due to urban models, don't have in hand. These parameters have to be included in future studies, in order to have the best solution for each case. Actually some of these systems have already been studied in the Task 53 - New Generation Solar Cooling and Heating Systems (PV or Solar Thermally Driven Systems). Seasonal storage will be needed in thermal systems and Net metering needs to be regulated in all the EU countries if we want NZEB.

4. Conclusions

FPC and PV with heat pump systems are a good solution for familiar households, both technologies are necessary in order to arrive to the future scenarios of zero emissions and net-zero energy building, and cover all the thermal demand. Net Zero thermal Energy Building are in Europe a technical and economic reality, with the expected future increase of the fossil fuel price and the reduction of the alternative technology costs. These new combisystems open new options to cover all the necessities of the houses with an optimized mix, which takes profit of the synergies of the different technologies.

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