Solar-Based Energy Technologies Potential to Meet a Hospital Energy Needs

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Abstract

This article analyses the potential of solar-based energy technologies to cover the electrical and thermal energy needs of a hospital. In particular, this work focusses on the case study of the *Hospital de Sant Pau*, in Barcelona, and it is based on previous work developed in the context of a research master's project at the UPC. Modular solar-based technologies available in the market are studied, as well as the weather conditions of the location and the hospital's energy demand. Three different solar-based technologies are identified as feasible to cover a percentage of the hospital energy needs: photovoltaic, thermal and hybrid solar panels. The potential of each one of the aforementioned technologies is studied separately; the number and distribution of each type of panels is calculated and their energy output throughout the year is calculated, by adjusting the orientation of the panels and the separation between the different rows. Once the yearly energy output for each technology is obtained, cost estimations and GHG emission savings calculations are conducted. The three alternatives prove to be economically viable and environmentally sustainable options for the case of study analysed, even if they can only cover a small percentage of the building's vast energy demand.

1. Introduction

One of the major concerns worldwide is climate change caused by global warming, and how to stop this temperature raise by eradicating, or at least mitigating, the greenhouse gases (GHG) emissions. Several countries have set as one of their main objectives the reduction of these gases on the short- and mid- term and the achievement of net-zero emissions on the long term.

In Spain, the installed power from renewable sources surpassed that of non-renewable sources in 2019, reaching a 50.1% of the total installed power in the country. This increment has been due mainly to the 89.2% increase in solar photovoltaic systems, which represent now an 8.1% of the installed power in the country. Solar thermal energy accounts for another 2.1% of the installed power, whilst the main renewable energy source in the country is wind power, representing a 23.4% of Spanish installed power [1]. In addition, about 38.9% of the 264,635 GWh of electrical energy generated in Spain in 2019 was obtained from renewable sources, according to *Red Eléctrica Española*. This percentage is slightly lower than that of 2018, since the hydraulic power plants generated a 28% less due to the low amount of precipitations. However, the rest of available renewable technologies

	2018	2019
PUMPED STORAGE	0.8	0.7
NUCLEAR	21.5	22.6
COAL	14.1	4.3
COMBINED CYCLE	10.7	20.7
COGENERATION	11.7	12.0
NON-RENEWABLE WASTE	0.9	0.8
RENEWABLE WASTE	0.3	0.3
WIND	19.8	21.5
HYDRO	13.8	10.0
SOLAR PHOTOVOLTAICS	3.0	3.6
SOLAR THERMAL	1.8	2.1
OTHER RENEWABLES	1.4	1.5

	2018	2019
RENEWABLES	40.2	38.9
NON-RENEWABLES	59.8	61.1

Figure 1. Electricity generation by source in Spain in 2018 and 2019 (Red Eléctrica de España, 2020a).

increased their production in a 10.5% in average in 2019. The electricity generation in Spain in 2018 and 2019 is shown in Figure 1, per source and in percentage over the total (Red Eléctrica de España, 2020a).

Another important fact in the Spanish electrical system is the substitution of an important part of coal- and fuel-powered generation (66% and 15% respectively) by combined cycle natural gas-fueled power plants. This technology is not renewable and accounts for more than a 40% of the greenhouse gases emissions of the electrical system, but its higher efficiency and far lower emission factor than that of coal- or fuel-powered power plants allows for a significant reduction of emissions (Red Eléctrica de España, 2020a; Red Eléctrica de España, 2020b).

Altogether, the emissions derived from the production of energy from coal, fuel and gas in Spain accounted for around 36.1 million tons of CO_2-equivalent in 2018, and 36.9 in 2019. This increase is almost negligible compared to the fact that these emissions were produced in the generation of a 28% more energy than in 2018 with these three technologies (Red Eléctrica de España, 2020a; Red Eléctrica de España, 2020b).

1.1. Energy consumption in buildings

Buildings are one of the biggest energy consumers worldwide, being responsible for about 40% energy and process-related GHG emissions (IEA, 2019; Nejat et al., 2015). In addition, worldwide buildings' energy demand is forecasted to continue growing in the coming decades (Husain et al., 2018), while buildings' GHG emissions must significantly decrease to be able to meet ambitions for a 1.5 °C world or below in 2050 (IEA, 2020; IPCC, 2018). In the European Union, the average yearly energy consumption for buildings is 180 kWh/m^2, and in Spain this number is slightly lower since it is located in the Mediterranean area's temperate climate (European Commission, 2020a).

From the above, the building sector is crucial for achieving global energy and environmental goals, therefore both energy efficiency in buildings and on-site renewable generation, are called to play a very important role in the next years (Un Environment and International Energy Agency, 2017; European Commission, 2019).

Among all types of buildings, hospitals are some with the highest energy consumption per surface unit, due to the fact that they work 24 hours a day and are equipped with high energy consumption equipment such as defibrillators, respirators, surgical units, amongst other machinery and equipment.

On the one hand, hospitals are generally located in -or very close to- urban areas, thus a renewable-based energy generation system in a hospital would not only lower the hospital's energy consumption and GHG emissions, but also those produced by the urban area where it is located. On the other hand, in urban areas, due to the high population density and low free space, most of the energy consumed is produced elsewhere. Consequently, this installation would not only reduce the external energy dependence of the hospital but also that of its area.

1.2. Modular solar-based technologies

There exist a number of renewable technologies but only a few present the potential for in-building clean energy generation. Among them, modular solar-based technologies, such as photovoltaic, solar-thermal, and hybrid photovoltaic-thermal technologies, are those presenting the greatest potential to allow on-site clean energy generation adapted to building designs (Attoye et al., 2017).

Solar Photovoltaic (PV) modules contain PV cells, that are electronic devices that allow electricity to be generated using solar energy. Given the reduced size of each PV cell, thus relatively low voltage and power output, they typically require to be connected to other cells in both series and parallel way to form a PV panel. These panels are usually put together in the form of solar photovoltaic arrays, that can be adapted to cover a particular area (Messenger & Abtahi, 2017).

Another way of harnessing sun power is to extract it in the form of heat. In fact, even if photovoltaic panels pretend to extract electricity from the incoming energy, they will always heat up as well, making solar thermal power an attractive idea. In solar thermal modules, a cold heat transfer fluid enters the panel and flows through metallic tubes underneath the glass cover, gathering heat from the sunrays, which is transferred to the fluid. This behavior is analogue for solar thermal modules that work with air or a mixture of water and glycol, which are the most common heat transfer fluids for these applications (The Renewable Energy Hub, 2020).

Finally, there is yet another technology that allows both thermal and electrical energy harnessing from sunrays. This is the case of hybrid photovoltaic-thermal (PVT) solar panels. This technology works essentially as a conventional PV panel with an added heat-collecting system (underneath the PV layer) which not only allows the extraction of thermal energy, but may also cool down the PV panel, increasing its efficiency (Ramos, 2017).

1.3. Aim and scope

This article aims to analyse the potential of solar-based energy technologies to cover the electrical and thermal energy needs of a hospital. In particular, the feasibility from the techno-economical point of view of the installation of three solar-based energy generating technologies in the *Hospital de Sant Pau*, in Barcelona, is addressed. This work is based on previous research developed in the context of a master's thesis at the UPC.

2. Hospital de Sant Pau

The chosen building for this study is *Hospital de la Santa Creu i Sant Pau*, in Barcelona. This hospital consists mainly in two areas. The first one is of Modernist style, with decorated, two-story separate buildings amidst gardens. This area, designed by the architect *Lluís Domènech i Montaner* and inaugurated in 1930, was declared World Heritage by UNESCO in 1997 (World Heritage Convention of the Unesco, 2020). The second area was built in 2009 on the northern edge of the hospital's terrain. This new hospital area consists of five higher blocks, each one dedicated to different medical activities. This distribution can easily be identified in Figure 2.

Figure 2. Aerial picture of the hospital area.

Since the modernist area of the hospital is a World Heritage Site, it must be preserved and not modified in any way. Consequently, this study will only consider the new hospital area (considering then its buildings, roofs and gardens) as possible sites for the installation of energy-generating solar-based technologies.

2.1. Hospital's energy demand

The hospital is connected to the electrical national grid, which currently supplies 100% of its electricity demand. The thermal energy demand of the hospital is covered partly by burning natural gas and partly by electricity. The data of the annual electrical energy and natural gas demands were obtained from the hospital. These demands are of 40,890,758 kWh(e) and 1,122,079 kWh(th), respectively.

Regarding the electrical load of the hospital, due to the lack of more detailed data, the consumption distribution of a hospital in Madrid (Pedrajas, 2017) has been used to extrapolate a load curve of a hospital and obtain an estimated load curve for *Hospital de Sant Pau*. The estimated monthly electricity consumption of the *Hospital de Sant Pau* is presented in Table 1.

Month	Load [kWh(e)]	Month	Load [kWh(e)]
January	3,333,988	July	4,215,156
February	2,810,292	August	3,953,564
March	3,102,922	September	3,456,845
April	3,230,887	October	3,451,627
May	3,357,586	November	3,332,027
June	3,656,430	December	2,989,435

Table 1. Electricity consumption per month.

In the case of the thermal load, there was no consumption profile available; the only known data was the natural gas consumption per year. Moreover, this amount of energy doesn't correspond to the global thermal energy demand, since the ratio between electrical and thermal demand established in (Mínguez, 2018) suggests that the thermal consumption of the hospital is around 12.75 GWh. This implies that the thermal energy consumed by the hospital is expected to be covered in around a 90% by electricity (such as electric boilers) and not only by natural gas.

3. Solar resource

The average annual global horizontal irradiation in Barcelona is about 1,610 kWh/m² (Global Solar Atlas, 2020). From the same source, Figure 3 showing the path of the sun throughout the year, especially considering the possible shade that the nearby environment may cause. Given the fact that the height of the new hospital is like that of the buildings nearby, they will not shade the panels as long as they are located on the roof of the hospital. Regarding hourly solar data of the hospital's location, it was obtained from (European Commission, 2020b).

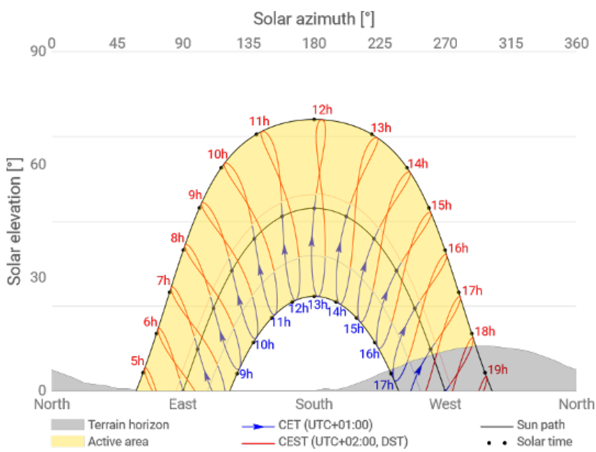

Figure 3. Trajectories of the sun throughout the year and shade of the nearby hills [18].

4. Solar technologies potential

Once obtained the energy demand of the hospital and the solar resource, in this section the potential of three different solar energy technologies to cover the *Hospital de la Pau* energy demand is analysed. The three different cases considered are: an installation based on PV panels, another based on solar thermal panels and a third one based on hybrid PVT panels.

4.1. Available area

The first thing that needs to be known to dimension the installation is the available area on which the panels can be installed. With this purpose, the various roofs of the hospital were analysed, considering whether they were suitable surfaces as to place a solar installation. The area of the different roofs which presents adequate characteristics was calculated, considering the shades that could appear during the day. In order to simplify the calculations, the shade was considered as if the sunrays were always coming from the southward direction. This will imply that, if an obstruction was placed at the Southwest of one of the roofs, the amount of energy calculated for the morning hours will be lower than the actual one, but in the afternoon the effect will be the opposite. In any case, the slight global difference throughout the day will be neglected.

The available roof areas have been then sketched and measured, using industrial drawings provided by the hospital, and obtaining the areas presented in Figure 4. All the areas identified as available -no shading- sum up 5,870 m^2.

4.2. Installation capacity calculations

In order to determine the power output of each technology, first calculations were to estimate the percentage of the surface that may be covered by panels. This was calculated in detail for the parts B1, C1 and

Figure 4. Available roof areas of the hospital.

D1. To begin with, the optimal separation between two rows of panels was found for area B1. This area faces south, making it easier to study, since all rows will have the same number of panels and will be perfectly aligned. The separation between rows needs to be considered, since their 38º inclination (optimal for the hospital's latitude) may cause the rows behind to be shaded. The panels will be fixed, and always facing South.

Calculations were made following the guidelines in Ikaskuntza Birtual eta Digitalizatuen LHII (2020) and considering that as soon as an area of the panel is shaded, the whole panel (and the rest of its row) are fully shaded. This was assumed since once a panel is partially shaded, its productivity drops drastically. Thus, once this happens, the output power was calculated for only the first row of panels. Once calculations are conducted for these three areas, the results obtained are extrapolated for the other areas. Further detail about these calculations can be found in Guerrero (2020).

Since the output power is always expected to be far lower than the hospital's consumption throughout the year, the aim of the calculations was to maximize the total energy output, though also considering the productivity of the panels. For all these calculations, dimensions and performance of state-of-the-art commercial solar panels were considered. For the PV panels the model chosen for these calculations was SunPower Maxeon 3 (Sun Power, 2020), for the solar-thermal (ST) panels, the model Baxi Sol 250H was selected (Gasfríocalor, 2020), and for the hybrid PVT panels Abora aH72 model was the chosen one (Abora Energy, 2020).

4.3. Results and discussion

From the calculations described above, and considering the information provided by the manufacturer of the solar panels selected, the total energy output and the energy output per panel was obtained. For the PV case, these calculations estimate that 1,193 PV solar panels of the selected model could be installed, which would produce about 716.3 MWh of electrical energy per year. This quantity represents a 1.75% of the current electricity demand of the hospital.

For the solar-thermal case, 941 solar panels of the selected model could be installed, which would produce about 2,738.0 MWh(th) of thermal energy per year. This quantity represents a 244% of the current natural gas demand of the hospital. This fact implies that, even in the case that this technology proved to be cheaper than the other technologies studied, a better solution would be to install it only on a part of the available surfaces and cover the rest with photovoltaic panels.

Results for the hybrid PVT case show that a total of 1,256 panels could be installed, producing an amount of 657.5 MWh(e) and 2,096.4 MWh(th) per year. Their productivity is around 523.5 kWh(e) and 1,669.1 kWh(th) per panel. These numbers imply a coverage of around a 1.6% of the electrical needs of the hospital, as well as a 187% of its natural gas consumption.

According to Pedrajas (2017), the energy consumption in a hospital of the size of *Sant Pau* and in the Mediterranean area is estimated to be of 25 MWh (69,4%) of electrical energy and 11 MWh (30,6%) of thermal energy, per bed and year. From data of *Hospital de Sant Pau*, we observe that more than 97% of the total energy demand corresponds to electricity consumption. From this data, it is safe to assume that an important part of the heating demand in the hospital is generated by electric heaters. This explains why in the cases of the installation of solar thermal and hybrid PVT panels, the thermal energy produced overcomes the hospital's demand. Assuming the electrical and thermal energy demands to follow the ratios of Pedrajas (2017), the annual electrical and thermal loads would be 29.2 GWh(e) and 12.8 GWh(th) -instead of 40.9 GWh(e) and 1.1 GWh(th)-, respectively. Considering those numbers, the percentages of energy covered in the three cases studied would be 2.46% (e), 21.37%(th) and 2.265(e)/16.37%(th) for the case of the PV, solar thermal and hybrid PVT installations, respectively.

5. Economic analysis

Once the output energy and productivity of the different options of installation have been calculated, the cost of these installations needs to be estimated, since it is also a parameter of paramount importance when it comes to decide which will be the selected installation option.

The chosen photovoltaic panel for this installation option is the SunPower Maxeon 3 (Sun Power, 2020). The price for the chosen PV panels has been estimated to be the same as the price of other panels with the same technical specifications, which is 158.98 € including a 5% VAT (Autosolar, 2020). The cost of the 1,193 panels would therefore be 189,663.14 €. According to Ramos et al. (2017) the cost of the panels accounts for a 58% of the total cost of a photovoltaic installation. Another 34% is attributed to the installation of those panels, whilst the remaining 8% of the total cost is related to the electrical components and fixing of the installation. Consequently, the cost of the electricity produced with this installation is 0.0183 €/kWh(e), which is much lower than the electricity price of the grid (of around 0.05343 €/kWh(e) for a hospital (OMIE, 2019). Since the installation is able to produce 716.3 MWh(e) per year, the savings will be around 38,271.91 €. Considering that the panels have a lifespan of around 25 years, the initial investment would be recovered in less than 10 years, and the net benefit would be 359,422.04 €. This production would imply an emissions reduction of around 3,433 tonnes of CO_2-eq in 25 years, according to Spanish electric grid's emissions rate (Red Eléctrica de España, 2020a).

The thermal panel that was selected for this option is Baxi Sol 250H (Gasfríocalor, 2020), with a cost of 635.01 €, including the VAT (Autosolar, 2020). The cost of the 941 panels of the installation in the hospital would then be 597,544.41 €. According to Walker (2013), the cost of an installed complete water heating solar system is approximately the double of the price of the panels, so the total cost of the system may be estimated at around 1,195,088.82 €. Altogether, the cost of the thermal energy generated by this installation would be around 0.0624 € kWh(th). This price is higher than the price of natural gas in Spain (13.5 €/MWh in 2019) (Guarracino et al., 2016), but despite of this, the annual savings regarding the previous natural gas purchase would be above 15,148.07 €. The initial investment would be also recovered in about 10 years, and the net benefits at the end of the panels' life (25 years) would be 1,428,723.52 €. The CO_2-eq emissions prevented by this system would be of 13,123 metric tons throughout the panels' lifetime; almost 4 times higher than in the case of the PV installation, due to the high emissions of natural gas boilers (Red Eléctrica de España, 2020b).

Finally, if the implemented technology is hybrid photovoltaic-thermal panels, the chosen panel is Abora aH72, which costs 568 € per panel according to the manufacturer (Abora Energy, 2020). The cost of the 1,256 installed panels will therefore be 713,408 €. Following the breakdown of the capital costs of a PVT installation established in Guarracino et al. (2016), the cost of the generated energy by these panels would be around 0.0765 €/kWh(e) if considering only the electrical output, and around 0.0240 €/kWh(th) if considering only the thermal output. The price per kWh of energy produced, combining electrical and thermal, is 0.0183 €/kWh. The initial investment is returned in less than 10 years, and at the end of panels' lifespan (25 years), the net revenue is 1,382,237.57 €. About the CO_2-eq emissions savings, these sum up 13,993 tons throughout the panels' lifetime, slightly higher than in the case of the solar thermal panels, and almost 4 times that of the case of the PV installation.

6. Conclusions

Among all types of buildings, hospitals are some with the highest energy consumption per surface unit, therefore to increase the percentage of their energy consumption that comes from renewable sources is of key importance. Modular solar-based technologies have been proven economically viable and environmentally sustainable options for on-site energy generation in the case of the *Hospital de la Pau* in Barcelona. For the three different type of solar-based generating installations studied (photovoltaic, solar thermal and hybrid photovoltaic-thermal panels), similar results are obtained in terms of payback time, that is about 10 years. Considering the three installations to have a lifetime of 25 years, the net revenue and the CO_2-eq emissions savings are almost four times higher in the case of the hybrid photovoltaic-thermal and solar thermal panels -about 1.4 M€ and 14,000 tons, respectively- than in the case of the photovoltaic installation.

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