Techno-economic assessment of solar technologies to meet hospitals energy needs

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ABSTRACT

Hospitals present one of the highest energy consumptions per surface unit, meaning that on-site renewable energy generation and energy efficiency improvements are key to lower hospitals energy demand, external energy dependence and greenhouse gases (GHG) emissions. In this work, the feasibility from the techno-economical point of view of the installation of three solar-based energy generating technologies in hospitals in different climate locations in Europe is addressed. The potential of solar energy technologies to cover the energy needs of the hospitals under study is conducted proposing a novel design and sizing optimization methodology for on-roof installations. The profitability of the different solar-based installations will vary depending on the solar technology output (electrical, thermal or both) and on the type of energy needs of the hospital; but in all cases, profitability is mostly influenced by the price of the current energy source supplying the hospital energy needs. Levelized cost of energy (LCOE) values for on-roof photovoltaic (PV), solar thermal (ST), and photovoltaic-thermal (PV-T) installations obtained are in the range of 0.028-0.056, 0.051-0.096, and 0.053-0.128 €/kWh, respectively; for locations in latitudes from 37 N (Seville) to 60 N (Oslo) in Europe. Results from this work aim to serve as reference for similar studies in a wide range of climates.

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1. INTRODUCTION

The energy sector is in transition worldwide due to the challenge to meet an increasing energy demand with the biggest share of energy coming from clean sources [1]. This is essential to accomplish climate ambitions and keep global temperature rise below 1.5 °C in 2050 [2], [3]. In 2019, the share of renewables in global electricity generation reached almost 27%, however renewable power must increase significantly to meet the sustainable development goals (SDGs) of 50% share of electricity generation by 2030 [4]. Solar PV represented about 5% of the electricity generation in 2019, that is almost 19% of the renewable electricity, and it is forecasted to account for 60% of the expected power capacity growth in the upcoming years [5]–[7]. Heating purposes add up to nearly 50% of the global energy consumption [8], [9], thus reaching a significant proportion of renewable heat is key to fulfill the aforementioned SDGs. However, only 10% of the worldwide heat comes from renewable resources, and solar thermal energy represents less than 10% of this percentage -thus less than 1% of the global heat consumption [7].

Solar energy presents the potential to provide a significant proportion of the renewable energy required worldwide while assuring energy supply security and independence, as a renewable globally distributed resource. Moreover, modularity of the majority of the solar-based energy technologies also allows their integration into the urban environment, something of quite importance when 70% of the world's population is projected to live in cities by 2060 [10]. Cities, or to be precise buildings, represent about 40% of the global energy consumption. About buildings greenhouse gases (GHG) emissions, despite following a downward trend, these still represent more than 30% of global process-related GHG emissions [11], [12]. Global buildings energy demand is forecasted to continue growing in the coming decades [13], [14]. Therefore, the building sector plays a key role to meet global environmental and energy goals, where both, energy efficiency in buildings and on-site renewable generation, are crucial [15], [16].

Hospitals are designed to operate 24 hours/day, they typically have large rooms and an elevate number of high energy consumption equipment. Thus, hospitals energy demand per surface unit is one of the highest among different types of buildings [17]. Since hospitals are in most cases located very close to urban areas, if on-site renewable energy generation possible, they would contribute to lower their own external energy dependence and GHG emissions as well as that of the surrounding area. Several authors have analysed hospitals energy consumption all over the world. Hourly, monthly and global energy consumption data of four hospitals in Spain are presented in [18]–[20]. Hospitals data presented in [20] also classified according to 3 different climatic zones. The 20 Spanish hospitals were analysed over a 10-year period, obtaining an average annual energy consumption of 0.27 MWh/m^2, 9.99 MWh/worker and 34.61 MWh/bed for Spanish hospitals and standard operating conditions [21].

Energy consumption of 13 Spanish private hospitals were studied in [22] resulting in an average annual energy consumption of 0.30 MWh/m^2, 9.10 MWh/worker, and 26.40 MWh/bed. According to the work in [23], maintenance management impact on a Spanish hospital bill is analysed, showing that an average annual increase of 6% in time spent on preventive maintenance operations, over a period of 5 years, resulted in a 20% decrease in the demand for corrective maintenance and resulting in an average annual savings of 500 MWh in energy consumption. Hospitals energy use in the UK is studied in [24], suggesting a process to evaluate the relevance of behaviour and other simple operational changes as tools for carbon mitigation in hospitals. Morgenstern [24] also discusses theoretical electricity savings potentials from simple operational changes, and these are found to be relatively small across 11 different hospital departments investigated.

According to the [25]–[27], data of energy consumption of a number of German hospitals is analysed, revealing that the average annual energy consumption of a hospital under normal climatic and operational conditions is 0.27 MWh/m^2, 14.37 MWh/worker, and 23.41 MWh/bed. The most suitable indicator to quantify the energy consumption of a hospital is proved to be the one dependent on the number of beds [27]. Exemplary best-practice solutions for relevant consumption sectors in hospitals are discussed in [28]. After analysing 20 average-size hospitals in Germany, it is concluded that replacing old, inefficient systems leads to significant savings and makes economic sense, however even new systems do not guarantee optimal energy consumption if operation parameters aren't optimised. Electrical consumption forecasting for hospital facilities in Italy is conducted in [29]; here authors consider an annual electricity consumption of 0.13 MWh(e)/m^2.

A number of initiatives towards reducing the electrical energy consumption of a Greek hospital are discussed in [30]; the hospital's average annual electrical consumption is 0.11 MWh/m^2. In [31] a tool to assess the energy consumption for heating and cooling in hospitals is developed, via modelling a defined room of a reference hospital in Athens which annual energy consumption is considered to be 0.19 MWh/m^2. A comparative analysis of Pacific Northwest and Scandinavian hospitals energy use is conducted, concluding that annual energy consumption for Scandinavian hospitals varies between 0.35-0.44 MWh/m^2, while this number can increase up to 0.78 MWh/m^2 for Pacific Northwest hospitals [32]. Moreover, for the majority of the cases, independently of the hospital's location, electricity consumption approximately corresponds to half of the total energy consumption. For the U.S., detailed hospitals energy consumption by type is presented in [33] and a global energy consumption distribution of healthcare facilities for several US climate zones is presented in [34].

The energy intensity of the U.S. hospitals ranges from 0.64 MWh/m^2 (very hot climate) to 0.78 MWh/m^2 (very cold climate), with an average of 0.74 MWh/m^2. The latter studies agree with numbers presented in [32], concluding that the energy intensity of healthcare facilities is higher in the U.S. than in most other countries, especially the European ones. Moving now to Asia, annual energy consumption of a Hospital in China -hot summer and cold winter location- is presented in [35]; being 0.11 Mwh(e)/m^2 the electrical consumption, and between 0.06-0.09 MWh(th)/m^2 its natural gas consumption. In [36] a comprehensive energy use study is conducted for hospitals in China, indicating that average annual total energy consumption goes from 0.34-0.38 MWh/m^2 depending on hospital size and electricity consumption represents the highest share about 64%. Equivalent numbers for a hospital in Taiwan are presented in [37]. In this case, the total averaged energy consumption over a year is 0.26 MWh/m^2. The annual energy consumption of a hospital in Korea is indicated to be 0.90 MWh/m^2, where, unlike in the previous cases, more than 85% corresponds to heat needs [38]. Authors of this work develop a load model to be applied in building energy system design and planning, to optimised energy consumption.

In Figure 1, the average annual energy consumption for a hospital per unit area in a number of countries/areas is presented. Data presented correspond to that obtained from the literature above; that even though can't be considered representative in all cases, it helps to show big differences in hospitals energy consumption depending on the location. These differences may be due to different climate conditions but also due to the ratio electrical/thermal energy demand, among others.

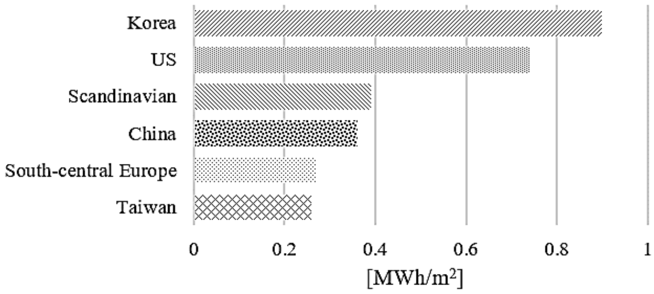


Figure 1. Annual average energy consumption of hospitals from revised literature

Finally, just a few studies were found addressing the integration of renewable-based energy generating systems and/or energy storage into a hospital building. A case study for a Belgium hospital is found in [39], were an aquifer thermal storage is considered, and the resulting energy balance of the building showed that the primary energy consumption of the heat pump system is 71% lower in comparison with a reference installation based on common gas-fired boilers and water-cooling machines, leading to significant CO_2 savings, and in [40] a solar-based poly-generation system for hospital buildings is designed and thermo-economically optimised. The dynamic simulation of the system is performed for a hospital located in Naples, Italy. Results of the simulation indicate savings of about 1.0 GWh of electrical energy, 1.5 GWh of cooling energy and 1.2 GWh of thermal energy (space heating and domestic hot water); these energetic savings correspond to a saving of about 253,000 €/year in terms of operating costs.

On the one hand, energy efficiency in buildings and on-site renewable generation is key to meet global environmental and energy goals in urban areas. On the other hand, solar-based energy generating technologies present a significant potential for on-site clean energy generation in buildings. Among the different solar-based technologies, solar photovoltaics (PV), solar-thermal (ST), and hybrid photovoltaic-thermal (PV-T) technologies, all present a key characteristic that facilitates their integration into the urban environment, their modularity [41]. PV solar modules contain PV cells, that are capable of electricity generation from the incident solar radiation on their surface. ST modules do not generate electricity but heat, by means of a circulating heat transfer fluid underneath a thermal absorber that is heated up due to solar radiation. Finally, PV-T modules combine both a PV layer and a thermal absorber and a circulating fluid, leading to a combined electrical-thermal output [42], [43]. All these three modular solar technologies are typically installed as a number of arrays that can be adapted to cover a particular area [44]. The number and type/s of modules to be installed will typically depend on the area available and on the energy demand and its characteristics. When the energy demand is 100% electricity, PV modules are the ideal solution provided the location has enough solar resource. The same happens when the energy demand is 100% heat, being ST modules the ideal solution in this case. However, buildings typically present both electricity and heat needs; as it is the case of hospitals. For these cases, the fraction electricity/heat, the hourly profiles of each type of energy demand and the solar resource available will define the best performing solar-based solution.

This work goes a step further than previous research and conducts a thorough techno-economic assessment of the potential of solar-based energy generating technologies to cover the electrical and thermal energy needs of three hospitals, each one in a different climate location in Europe. In particular, the hospitals studied are: a hospital located in Oslo (Norway), one in Turin (north of Italy) and one in Seville (south of Spain). The feasibility of three solar-based energy technologies (photovoltaic, solar thermal, and hybrid photovoltaic-thermal) in the aforementioned hospitals is addressed. For the solar-based on-roof installations design and sizing optimization a novel in-house developed methodology is proposed. Moreover, from the economic assessment the levelized cost of energy (LCOE), among other economical parameters, of each solar-based installation for the different latitudes is obtained. Results from this work aim to serve as reference for similar studies in a wide range of climates.

2. METHOD
2.1. Solar resource at the selected locations
The locations of the three hospitals that have been selected for this study are: Oslo (Norway), Turin (Italy), and Seville (Spain). In Figure 2, the global solar irradiation on optimally-inclined south-oriented surface at the selected locations is presented [45]. The average annual global horizontal irradiation (GHI) in Oslo is 952 kWh/m^2 and the Global tilted irradiation at optimum angle (GTIopt) is 1204 kWh/m^2. In Turin, GHI and GTI_{opt} values are of 1401 and 1697 kWh/m^2, respectively. And for the location of Seville, irradiance values are the highest being the GHI and GTI_{opt} of 1839 and 2123 kWh/m^2, respectively [46].

For the calculations presented in this work hourly detailed irradiance data including direct normal irradiance (DNI) and diffuse horizontal irradiance (DHI), among others, as well as ambient temperature or wind velocity, are considered. These data have been obtained from database [45], and information related to the hourly sun's position, the azimuthal and zenithal angle of the sun throughout the year, has been obtained from [47]. From the detailed solar irradiance data and sun's position the hourly global irradiance on the corresponding tilted surface for each location is calculated [48]. Detailed temperature and wind velocity data will be used to calculate the solar panels temperature for precise calculation of its operating efficiency.

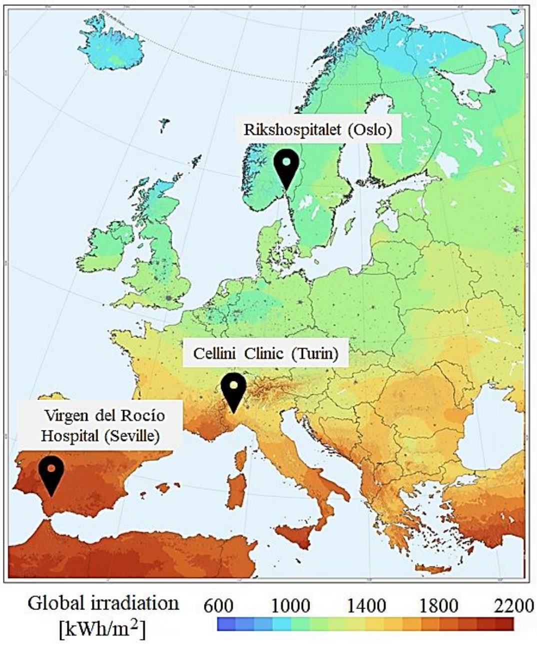


Figure 2. Yearly sum of global irradiation on optimally-inclined south-oriented surface in kWh/m^2 in the three selected locations [45]

2.2. Hospitals data
For this study, three average-size hospitals located in three different climate locations have been selected. The climate locations of this study are: Rikshospitalet in Oslo (Norway), Cellini Clinic in Turin (Italy) and Virgen del Rocío University Hospital in Seville (Spain). Each case of study and its energy demand is presented below.

2.2.1. Rikshospitalet (Oslo)
Rikshospitalet was built in 2001 and it is a National University research hospital that serves specialized patients from all over Norway. Rikshospitalet has 712 beds and an average energy consumption per year of 438.5 kWh/m^2. Currently, 100% of the hospital electricity demand is covered by the electrical national grid. The thermal energy demand of the hospital is covered partly by burning oil (oil boiler) and partly by electricity (electric boiler). The total electricity, oil boiler and electric boiler energy demands are 39,652,832 kWh(e), 19,042,670 kWh(th), and 29,711,869 kWh(e), respectively. Its detailed energy consumption per month over the year is presented in Figure 3 [32].

Since this work will address the energy balance of the cases of study for each hour of the year, hourly energy consumption profiles are calculated. In the case of Rikshopitalet only total monthly data is available, thus in order to obtain electrical and thermal hourly energy demands the hourly consumption for an average week of a hospital presented in [18] is considered. From these data, both the electrical and thermal load curves of the hospital are extrapolated as follows. The hourly consumption throughout an average week in [18] was expressed as percentages of the whole week load; in this way, the percentage of consumption that each day represents regarding the week total load can be obtained. With these data, the hourly power consumption profile throughout a week could be found for each month. As an example, the hourly profile of an average week for the total energy demand in January, April, July, and October is shown in Figure 4.

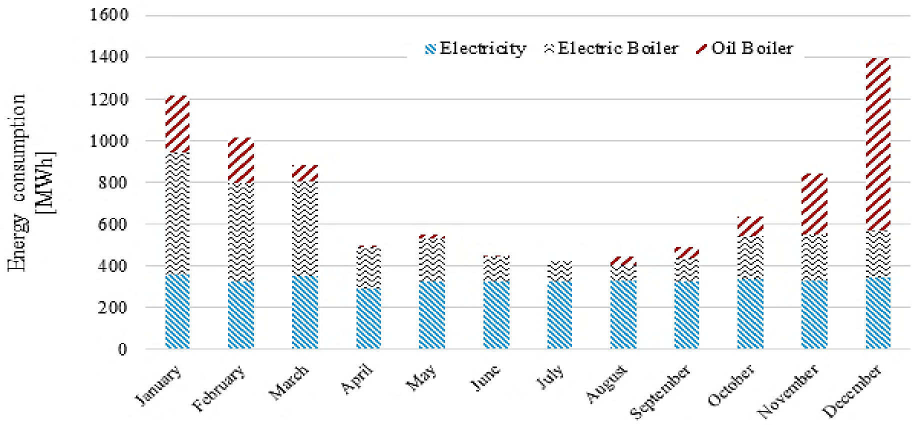


Figure 3. Energy consumption per month over the year for Rikshospitalet [32]

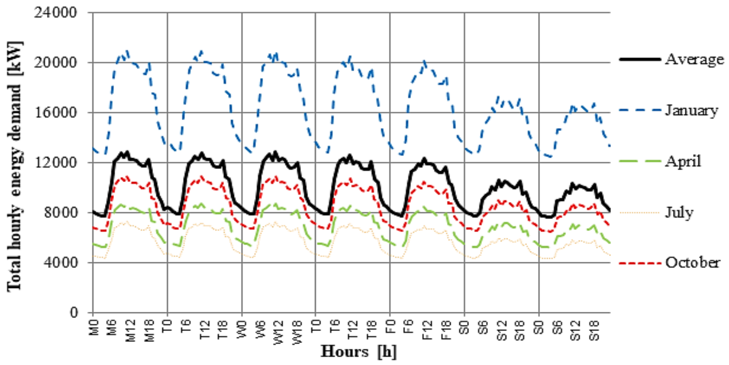
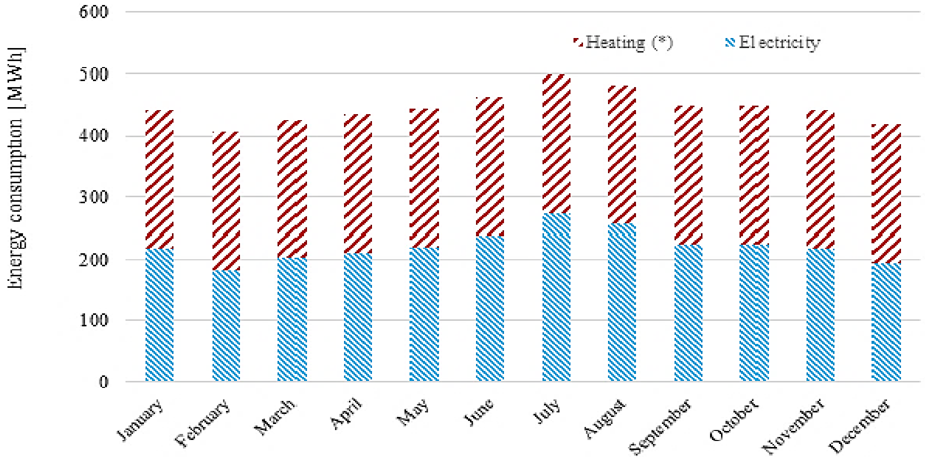


Figure 4. Calculated hourly profile of an average week for the total energy demand for Rikshospitalet [32]

2.2.2. Cellini Clinic (Turín)

The Cellini Clinic is a multi-specialist hospital facility part of the "Humanitas Mirasole" group in Turin, Italy. Its service started in 1903, and it was in 2003 when the Clinic received the accreditation by the National Health Service. It is divided into three main building blocks covering a total area of 9,500 m^2 [29]. The electricity needs of the Cellini Clinic are provided by its connection to the national electrical grid and its yearly electric energy consumption is of nearly 3 million kWh(e) (2,662,325 kWh(e) in 2012); which results in an average electricity consumption per unit area of 131,1 kWh(e)/m^2 [29]. The thermal energy demand of the Clinic is estimated assuming that its thermal energy consumption per square meter is similar to that of a hospital of the same size in the continental area of Spain (similar climatic conditions), resulting in an average thermal energy consumption per unit area of 148,9 kWh(th)/m^2 [20]. Due to the lack of monthly detailed data, the monthly electricity consumption of the Cellini Clinic is assumed to also follow the monthly load curve of a hospital in the continental area of Spain [18], and the thermal energy demand is assumed to be constant over the year. The latter assumptions may differ from the real load curve of the hospital, mainly depending on the equipment (electrical or thermal-fed) used to cover the heating needs, but it will be useful to have an estimated thermal energy consumption per month to be compared with the monthly generation calculations presented in section 5. Cellini Clinic detailed energy consumption per month over the year is presented in Figure 5.

Regarding the hourly profile of an average week for the total energy demand of the Cellini Clinic, it has been calculated considering that the Clinic follows the hourly profile in [18]. Therefore, obtaining an hourly profile equivalent to that presented in Figure 4 for the case of Rikshospitalet (Oslo); which agrees with the hourly profile for the Cellini Clinic presented in [29].



(*) Heating consumption has been distributed equally over the year due to the lack of more detailed data; thus, not reflecting the real thermal load curve of the clinic

Figure 5. Estimation of energy consumption per month over the year for the Cellini Clinic

2.2.3. Virgen del Rocío University Hospital (Seville)

The Virgen del Rocío University Hospital is located in the center of Sevilla city (Spain). It is one of the most important hospitals in the South of Spain, being the biggest hospital in the region. It was opened in 1955, and nowadays it has over 8,000 professionals, 54 surgery rooms, 1,291 beds, and 450 clinical consultation rooms [49]. The overall energy consumption of the Virgen del Rocío Hospital in 2017 was of 71,138 MWh: 63.8% (44,692 MWh) electricity, and 37.2% (26,446 MWh) of fossil fuels consumption to cover thermal energy needs [50]. This electricity-thermal energy consumption ratio is also in agreement with hospital loads in Spain by climatic area [20], [22]. Due to the lack of more detailed data, the monthly electricity consumption of Virgen del Rocío Hospital is assumed to follow the monthly load curve of another Spanish hospital nearby of which this information is available [18]. In the case of the thermal load supplied by fossil fuels, it is mainly devoted to cover domestic hot water (DHW) and other hospital services needs that are fairly constant over the year; note that heating needs are very low in this case due to the location warm weather and when existing they are covered by an electricity-fed heat pump system. Therefore, the thermal load of the Virgen del Rocío Hospital is estimated to be approximately constant throughout the year. Its detailed energy consumption per month over the year is presented in Figure 6. The hourly profile of an average week for the total energy demand of the Virgen del Rocío University Hospital is calculated considering it to be equivalent to that of the cases of Rikshospitalet (Oslo) and Cellini Clinic (Turin).

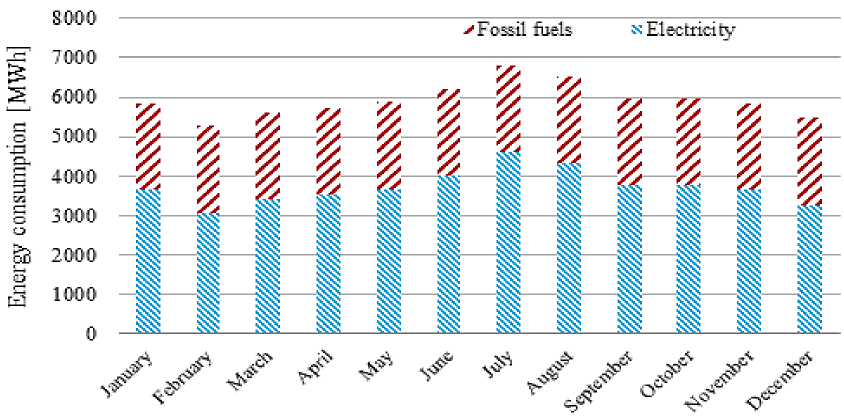


Figure 6. Estimation of the energy consumption per month over the year for Virgen del Rocío University Hospital

2.3. Commercial solar panels

For all the calculations below dimensions and performance of state-of-the-art commercial solar panels are considered. For the case of the solar PV panels, a PV panel among the best-performing ones in 2020 of the company SunPower was chosen, the Maxeon 3 [51]. Its size is 104.6×169 cm, its nominal efficiency 22.6% and its warranty period is of 25 years [52].

Regarding solar-thermal (ST) panels, a state-of-the-art flat-plate solar thermal collector is selected. The model VITOSOL 200 is chosen as representative collector of those in the market [53]. VITOSOL 200 dimensions are 238×105.6 cm. Efficiency of these type of collectors varies between 75 to 60% for collector temperatures from 20 to 50 °C above ambient temperature [54].

Finally, for the hybrid PV-T panels, a model among the best performing flat-plate PV-T is selected: Abora aH72 [55]. Its dimensions are 197×99.5 cm, that correspond to standard dimensions of these type of panels, however in this case the market is much smaller while a bigger variety of designs and sizes can be found. Abora aH72 PV design and size correspond to the average of these solar hybrid panels, and its photovoltaic and thermal nominal efficiencies are 18.7% and 70%, respectively.

2.4. Installation design

The installation capacity and energy generation potential of three different solar-based technologies, photovoltaic (PV), solar thermal (ST), and hybrid photovoltaic-thermal (PV-T), is evaluated in the three cases of study. It's worth mentioning that for all cases, the output power is expected to be significantly lower than the hospitals energy consumption over a year. Then, the aim of the calculations is to maximize the total energy output for each one of the technologies evaluated. Hourly simulations of each solar-based system performance for a full year period are conducted for both the installation design optimization and the energy generation calculations.

The installation design of the three modular solar energy technologies PV panels, solar-thermal panels and hybrid PV-T panels- is conducted following these steps. Firstly, the roof available area for the installation of solar panels is estimated. Secondly, the optimum tilt angle of the solar panels is calculated for each location according to their latitude aiming to maximize annual energy generation over a full year (assuming fixed panels south-oriented). Then, the calculation of the optimal separation between two rows of panels in both vertical and horizontal position is conducted. The panels tilt angle will change depending on the hospital location, accordingly with location irradiance data. Thus, separation between rows needs to be considered to avoid any row to be shaded. Finally, the energy output for each modular solar-based technology is obtained.

For the calculations regarding optimal separation between rows of panels, it is assumed that there is no energy output when any part of the solar panel is shaded; worst case scenario [56]. Then, the energy generation estimation will be lower than in a real case; and to a greater extent for the thermal output of the ST and PV-T panels. In any case, the shading will occur when the sun's elevation (and therefore the solar incident irradiance) is low; thus, the mismatch is expected to be of low significance.

For the energy output calculations, the solar panels efficiency curve (from the manufacturer) and hourly weather data [45], are considered. In (1) the expression for the PV panels efficiency is presented, where the η_{PV_0} is the nominal PV efficiency, β is the temperature coefficient, T_{PV} is the PV panel temperature and T_{STC} is the standard testing condition temperature. The thermal efficiency of a ST or PV-T collector can be expressed as indicated in (2)-(3). Where the η_{TH_0} is the nominal thermal efficiency, a_1 and a_2 are the first and second heat loss coefficients, T_{red} is the reduced temperature, G is the global incident irradiance on the panel, T_{Panel} is the mean solar panel temperature [57].

$$\eta_{PV} = \eta_{PV\_0}\,[1 - \beta\,(T_{PV} - T_{STC})] \tag{1}$$

$$\eta_{TH} = \eta_{TH\_0} - a_1 T_{red} - a_2\, G\, T_{red}^2 \tag{2}$$

$$T_{red} = (T_{Panel} - T_{amb})/G \tag{3}$$

The conversion efficiency of the solar-based technologies will vary with the operating temperature. Thus, this temperature is estimated for the case of the PV technology following the correlation presented in (4), where the solar panel temperature depends on the global horizontal irradiance (GHI), ambient temperature (T_{amb}) and wind velocity (v_{wind}) [58].

$$T_{Panel} = (0.943\, T_{amb}) + (0.0195\, GHI) - (1.528\;\; v_{wind}) + 0.3529 \tag{4}$$

For the cases of the ST and PV-T technologies, the average panel temperature is considered to be the mean temperature between the heat transfer fluid (HTF) inlet and outlet temperatures. Moreover, the inlet HTF temperature is considered to be that of the water mains of each location, and the outlet temperature is set to 60 °C. Averaged water mains temperature over the year of each case of study location is 8, 13 and 16 °C for Oslo, Turin, and Seville, respectively [59]–[61]. Data regarding the roof available area estimated for the installation of solar panels for each one of the three hospitals under study is presented in Table 1. The optimum tilt angle of the solar panels calculated for maximum annual energy generation and for each location is also presented in Table 1.

Table 1. Estimation of the roof area available and calculated optimum tilt angle for the solar panels for the three cases of study

Hospital	Location	Available roof area [m^2]	Panels optimum tilt angle [°]
Rikshospitalet	Oslo (Norway)	16,400	46
Cellini Clinic	Turin (Italy)	1,066	39
Virgen del Rocío	Seville (Spain)	39,350	35

2.5. Design optimization

Hourly calculations over a full year are conducted. The optimization is addressed calculating the best-performing separation between rows of panels. For the later, a compromise solution between the maximum possible energy generation per solar panel and over a year must be sought, since these two parameters won't reach a maximum for the same installation capacity. The maximum energy generation per panel will occur when there is no shading of one row on another, while the maximum total yearly generation is likely to occur increasing the number of panels installed, although there may be some shading between rows. Both, vertical and horizontal positioning of the solar panels is also considered for the design optimization. The energy output per panel and the yearly energy output (for both vertical and horizontal positioning of the solar panels and different panel rows separation) is calculated for each hour of the year, for each case of study and for each solar-based technology.

In Figure 7 an example of the solar panels positioning for a given roof area and orientation considered for the design optimization is presented. In calculations conducted to obtain the number of solar panels installed per case of study and solar technology the real dimensions of the commercial modules selected as well as free space to access all the panels for maintenance needs are considered.

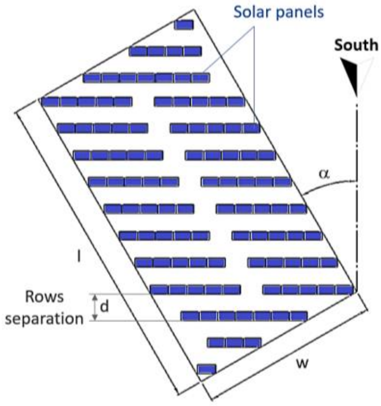


Figure 7. Example of the solar panels positioning for a given roof area and orientation considered for the design optimization

In Figure 8, the yearly energy output per panel and the total energy output for the installation of PV solar panels on the Rikshospitalet's (Oslo) roof as function of the solar panel rows separation are presented. These calculations have been conducted for one representative roof area available at Rikshospitalet and are shown as an example. It can be observed how the solar panel productivity increases with the separation between rows, while the yearly output reaches a maximum for certain conditions. It is worth mentioning that the fluctuations (peaks) that can be observed in the curves above are due to the consideration of integer numbers of panels and panel rows for these calculations.

Each pair of colored diamonds in Figure 8 represent one of the possible candidates to an optimal design. Their values together with the number of solar panels and the separation between panel rows for a representative area of Rikshospitalet are presented in Table 2. Regarding the PV panels yearly output, it seems to be slightly higher for the case of a vertical positioning, and in both of these cases the panel productivity is also a bit higher than that of the horizontal positioning. Furthermore, among the vertical positioning options, the first one (red diamonds) presents a significantly higher panel productivity than the other one; thus, being the installation design selected. This design considers 150 PV panels installed in parallel rows 3.7 m separated.

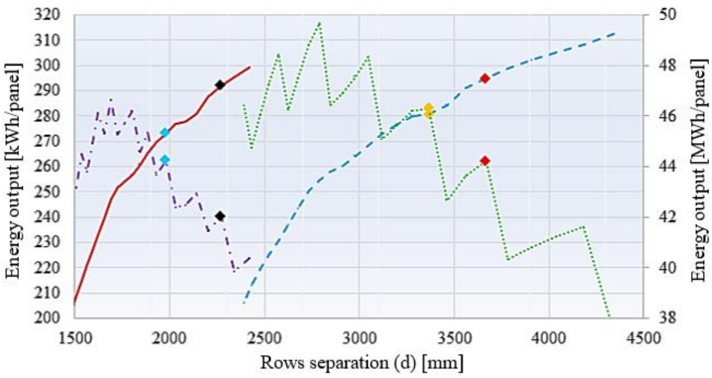


Figure 8. Rikshospitalet case study: power output per PV panel (blue dashed line (vertical) and continuous red line (horizontal)) and yearly power output (green dotted line (vertical) and purple dash/dotted line (horizontal)) for separations between solar panel rows (d) from 1.5 to 4.5 meters

Table 2. Best combined performance designs for a representative roof area of Rikshospitalet (Oslo) and final installation design selection

Vertical/Horizontal	PV output [kWh/panel]	PV output [MWh/year]	Number of PV panels	Distance between rows [m]
Vertical (selected)	294.88	44.23	150	3.666
Vertical	280.67	46.31	165	3.367
Horizontal	291.98	42.05	144	2.269
Horizontal	273.12	44.24	162	1.979

3. RESULTS AND DISCUSSION

3.1. Energy results

The same procedure explained in subsection 2.5 has been followed to obtain the optimum installation designs for the case of ST and PV-T panels in Rikshospitalet. In Table 3, a summary of the selected PV, ST, and PV-T installation designs and the complete system performance for the total roof area available is presented. Here, useful energy output per panel and over the year is presented. The difference between these values and those presented in Table 2 for the PV output is that 15% of overall losses (inverter efficiency, dirtiness and wiring losses), in addition to those due to shading and PV operation temperature that have been already considered in the generation calculations presented in section 2, are now taken into account to estimate the useful energy output of the complete installation [62], [63]. Regarding the thermal output of the ST and PV-T installations, heat losses along the piping system together with storage and heat exchanger efficiencies are also considered in the calculation of the useful energy output; meaning that roughly 40% of the thermal energy generated by the solar panels reaches the end user [64], [65].

Table 3. Summary of the selected PV, ST, and PV-T final installation designs and their performance for the case of Rikshospitalet

Rikshospitalet (Oslo)						
Solar technology	Vertical/Horizontal	Useful energy output [kWh/panel]	Total useful energy output [MWh/year]	Total number of panels	Installed capacity [MW]	Distance between rows [m]
PV	Vertical	250.6 (e)	1036.1 (e)	4134	1.653 (e)	3.666
ST	Vertical	536.9 (th)	1553.7 (th)	2894	5.936 (th)	5.499
PV-T	Vertical	224.8 (e) 221.7 (th)	892.1 (e) 879.8 (th)	3969	1.389 (e) 5.446 (th)	4.150

Following the same procedure described above for the case of Rikshospitalet in Oslo, the optimum installation design is obtained for the cases of the Cellini Clinic in Turin and the Virgen del Rocío University Hospital in Seville, for each solar technology. In Tables 4 and 5, the optimum installation designs and their performance for the Cellini Clinic and Virgen del Rocío Hospital, respectively, are presented.

Table 4. Summary of the selected PV, ST, and PV-T installation designs and their performance for the case of the Cellini Clinic

Cellini Clinic (Turin)						
Solar technology	Vertical/Horizontal	Useful energy output [kWh/panel]	Total useful energy output [MWh/year]	Total number of panels	Installed capacity [MW]	Distance between rows [m]
PV	Vertical	441.7 (e)	101.6 (e)	230	0.092 (e)	3.946
ST	Vertical	963.6 (th)	148.4 (th)	154	0.315 (th)	5.751
PV-T	Horizonal	379.8 (e) 483.4 (th)	78.24 (e) 99.6 (th)	206	0.072 (e) 0.283 (th)	2.323

Table 5. Summary of the selected PV, ST, and PV-T installation designs and their performance for the case of the Virgen del Rocío Hospital

Virgen del Rocío Hospital (Seville)						
Solar technology	Vertical/Horizontal	Useful energy output [kWh/panel]	Total useful energy output [MWh/year]	Total number of panels	Installed capacity [MW]	Distance between rows [m]
PV	Vertical	505.8 (e)	6346.1 (e)	12547	5.019 (e)	2.719
ST	Horizontal	1019.6 (th)	8339.6 (th)	8179	16.727 (th)	1.798
PV-T	Vertical	447.3 (e) 637.5 (th)	4333.0 (e) 6176.5 (th)	9688	3.391 (e) 13.305 (th)	3.571

In Figures 9-11, the useful total energy delivered per solar installation over a year for each one of the three locations under study is presented. Since all the solar installations where designed aiming to maximize solar panels annual productivity, they reach their peak of energy generation in summer; except for the case of Seville, where the very high temperatures during July and August and the good weather in September-October delays the peak a couple of months. The winter season is in all cases the period with the lowest productivity. It can be also observed that in all of the cases the installation delivering the biggest amount of energy almost every month of the year is the PV-T one, followed by the ST installation. The ST installation is the one delivering the biggest amount of energy for a few months in winter in the locations of Oslo and Turin, when the incident solar irradiance is very low. The latter it is explained due to the stronger effect of low incident irradiance on the PV performance that affects both the PV and PV-T installations. Moreover, in all cases the PV generates the lowest energy output, as expected given its lower conversion efficiency.

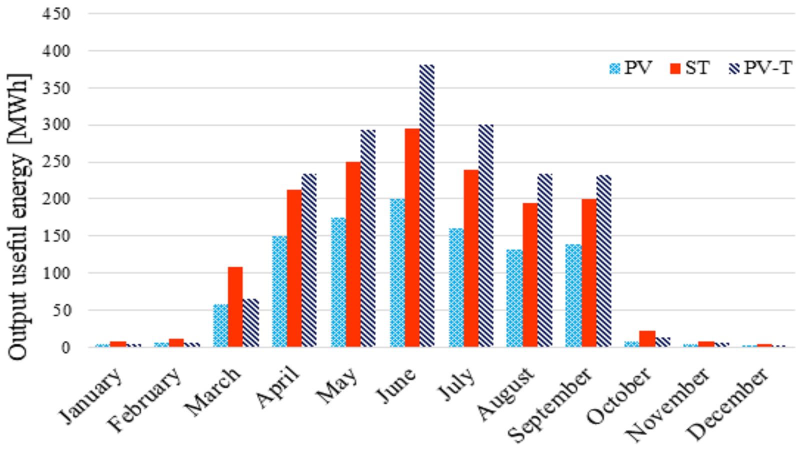


Figure 9. Energy generation per solar installation over a year for the case of Rikshospitalet (Oslo)

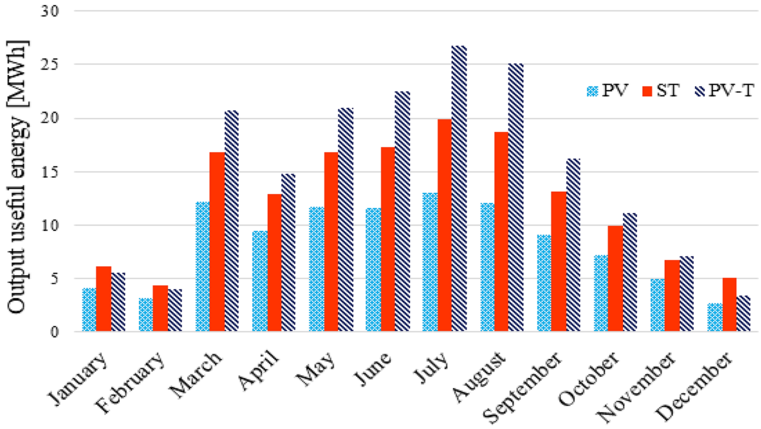


Figure 10. Energy generation per solar installation over a year for the case of the Cellini Clinic (Turin)

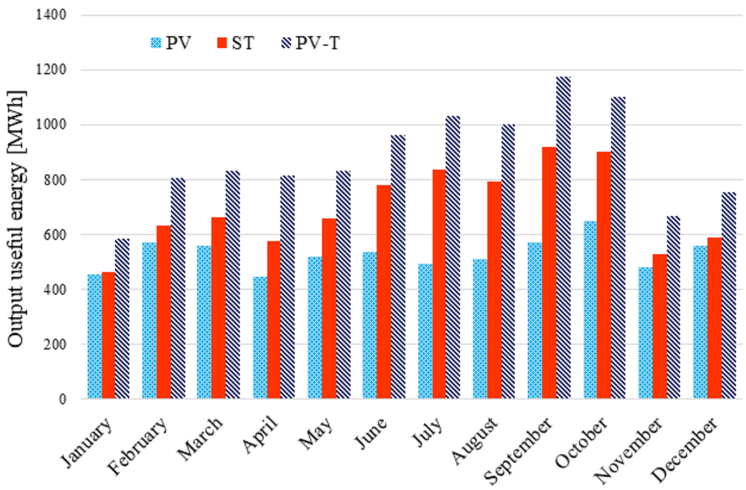


Figure 11. Energy generation per solar installation over a year for the case of Virgen del Rocío University Hospital (Seville)

The roof area available for solar panels installation varies depending on each one of the hospitals analyzed (see Table 1). Therefore, the roof area available limits the maximum energy generation (no matter which technology is selected) and, consequently, the percentage of the energy demand of the hospital that could be covered. The type of energy demand (i.e. percentage of electrical versus thermal energy) would also influence the profitability of the installation of each different solar technology. For example, in the case of Rikshospitalet (Oslo) the lowest energy demand occurs from May to September, which corresponds to the months with the highest solar energy generation. In addition, during these months in Rikshospitalet practically all of the electrical and thermal needs are covered by electricity (see Figure 3). The latter means that to install either ST or PV-T technologies may not be profitable since all the thermal energy output would be lost during these months, so the only solar installation that seems feasible would be the one only generating an electrical output: the PV installation. Moreover, the PV installation for the case of Rikshospitalet would only cover about 2.6% of the electrical demand over the year (4-6% during the months of April-September).

For the cases of the Cellini Clinic (Turin) and Virgen del Rocío University Hospital (Seville), both present a significant electrical and thermal energy demand every month of the year, and the amount of energy generated is also always far below the hospital energy needs. Given the small size of the Cellini Clinic, thus the area available for the solar-based technologies installation, the PV installation in Turin could only cover about 3.8% of the total electrical demand, the ST installation could cover 5.5% of the thermal energy needs and the PV-T installation about 3.3% of the overall energy demand over a year. Accordingly, for the case of the Virgen del Rocío Hospital, with a total energy demand similar to that of Rikshospitalet but much larger area available for the installation of solar technologies, the PV installation could cover about 14.2% of the total electrical demand, the ST installation could cover 31.4% of the thermal energy needs and the PV-T installation about 14.8% of the overall energy demand over a year.

Aiming to compare these results, in Table 6 the amount of energy delivered yearly per unit of roof area available for the solar installation for the three cases of study is presented. It can be observed that in all cases, the amount of energy delivered per unit of roof available is greater for the case of the PV-T installation, followed by the ST and PV installations. In addition, when moving to lower latitudes the productivity per unit of roof area increases as expected. However, in order to truly compare these different solar-based installations not only the energy delivered but the cost per kWh generated must be calculated. Thus, economic calculations of the solar energy installations above are addressed in section 6.

Table 6. Amount of energy delivered per unit of roof area available for each case of study and each solar technology

Solar technology	Useful annual energy output/roof area available [kWh/m^2]		
	Rikshospitalet (Oslo)	Cellini Clinic (Turin)	Virgen del Rocío Hospital (Seville)
PV (e)	63.2	95.3	161.2
ST (th)	94.7	139.2	211.9
PV-T (e+th)	108.0	166.8	267.2

3.2. Economic analysis and discussion

From the calculated yearly useful energy output and productivity of the three different solar-based energy-generating complete installations, the installation costs are evaluated. The aim of this section is not only to obtain the cost per kWh delivered for each solar system and location, but to give a range of levelized cost of energy (LCOE) values that may serve to extrapolate these results to a wide range of locations.

The cost of the PV panel selected (SunPower Maxeon 3 [51]) is about 160 € and the cost of the PV panels is estimated to account for 35-58% of the total cost of an on-roof photovoltaic installation. About 30% of the total installation cost corresponds to the panels installation and system balance, 4-6% is attributed to the inverter and the remaining part of the total cost is related to other electrical components, fixings and additional system costs [8], [66]. For economical calculations below, it has been considered that the cost of the PV panels of the installations studied is 45% of the total cost of the system. Known the number of panels to be installed in the case of study of Rikshospitalet (Oslo) and the yearly useful energy output, the cost per unit of energy delivered is 0.056 €/kWh(e) for 25 years lifetime (0.071 €/kWh(e) for 20 years). In the case of the Cellini Clinic (Turin) this number improves due to the higher solar irradiation, being the cost per unit of energy 0.032 €/kWh(e) for 25 years lifetime (0.040 €/kWh(e) for 20 years). In any case, the lowest cost per unit of energy delivered is obtained for the Virgen del Rocío University Hospital in Seville, whose location presents the best irradiation data among the cases studied. For this hospital, the cost is 0.028 €/kWh(e) for 25 years lifetime (0.035 €/kWh(e) for 20 years). These numbers are in the order of magnitude of those for the cost of commercial rooftop solar PV (up to 500 kW) installed in 2019, which were between 0.056 and 0.237 €/kWh(e); and with the global average LCOE of utility-scale PV in 2019 was 0.061 €/kWh(e) [67]. Regarding the cost per Wp installed for the three cases of study, it is of 0.88 €/Wp. This cost is the same for the three different locations since same PV panels and installation costs are assumed. In 2019, the lowest cost per Wp reported for on-roof installations decreased up to 0.74 €/Wp, being the cost that is expected to continue a downward trend [67]. The cost of on-roof PV installations is still above of on-ground state-of-the-art PV ones, that in 2019 presented an average cost (EU market) of 0.35 €/Wp [68].

Regarding the ST collectors and the thermal energy cost, the cost of the ST panels considered is about 650 € [53], and the ST panels cost is assumed to be about half of the overall installation costs; being the rest of the installation (piping, short-term thermal energy storage (TES), and installation) the other half [69]. Thus, the cost per thermal energy delivered, for 25 years lifetime, is 0.096 €/kWh(th) in the case of Rikshospitalet (Oslo), 0.054 €/kWh(th) in the case of the Cellini Clinic (Turin), and 0.051 €/kWh(th) for Virgen del Rocío Hospital (Seville) (0.121 €/kWh(th), 0.067 €/kWh(th) and 0.063 €/kWh(th) for 20 years lifetime, respectively). The size of these installations (solar panels area) 6714, 357 and 18956 m^2, respectively. Figures published by the International Energy Agency via the 'IEA SHC Task 52: solar heat and energy economics in urban environments' [70] indicate that the cost of an on-roof solar-thermal installation in northern/central Europe of 500–5,000 m² is estimated to be between 0.073 and 0.112 €/kWh(th) [71], [72]; thus, in agreement with the numbers obtained above.

Regarding the PV-T installations, the following calculation has been conducted to estimate the cost per unit of energy generated. From information in [8], [73], [74] -and checking current market prices of a PV-T and ST panels- the price of a state-of-the-art PV-T panel is in average about 48.8% higher than that of a ST panel, per unit area. In addition, in [73], the breakdown of the capital cost of a PV-T installation is presented, being the PV-T panels responsible of about 57% of the total cost, installation of the 17% and piping, fixings, short-term TES, and others, of the 26% left. In the case of a ST installation the cost of the ST panels is about 50% of the total cost, then, the total cost of a PV-T installation is considered to be 30.5% higher than the cost of a same size ST one. Therefore, the cost of the overall energy delivered, for 25 years lifetime, is 0.128 €/kWh in the case of Rikshospitalet (Oslo), 0.066 €/kWh in the case of the Cellini Clinic (Turin) and 0.053 €/kWh for Virgen del Rocío Hospital (Seville) (0.159 €/kWh, 0.082 €/kWh and 0.066 €/kWh for 20 years lifetime, respectively). If taking into account the ratio electrical-thermal energy output delivered the cost of the electricity is 0.254, 0.150 and 0.128 €/kWh(e) and the cost of the thermal energy is 0.257, 0.118 and 0.090 €/kWh(th) for the locations of Oslo, Turin and Seville, respectively (25 years lifetime). About PV-T systems costs, scarce information has been published, and when found it is for small scale installations. In [73] the LCOE is calculated for a small scale PV-T system in a hot and cold climates. The electricity goes from 0.19 to 0.46 €/kWh(th) while the thermal energy cost varies between 0.28 and 0.76 €/kWh(th); however, these numbers are hardly applicable to this study due to the different installation sizes.

In Figure 12, the LCOE obtained for the three different solar technologies studied depending on the case study location is presented. It is worth mentioning here that for the economic calculations above no subsidies or financial aid that may be available for this type of facility in the different countries under study has been considered. Thus, the values presented below can serve as reference for equivalent solar on-roof installations in a wide range of locations depending on their latitude.

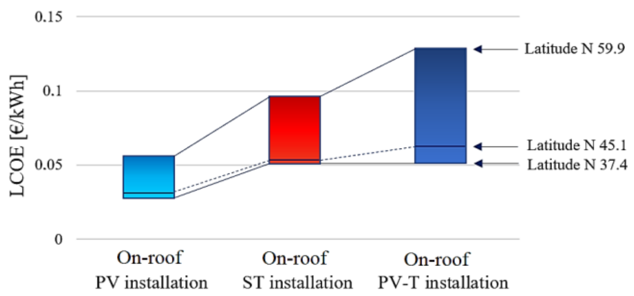


Figure 12. Obtained LCOE in €/kWh for on-roof solar installations depending on the location latitude

Finally, considering electricity and fossil fuels prices for the three locations under study and an average solar-based system lifetime time of 25 years the payback time (PBT) is estimated. Average electricity cost, including taxes, during the first half of 2021 have been considered for non-household consumers for Norway, Italy, and Spain; being the average electricity price of 0.080, 0.158, and 0.107 €/kWh, respectively [75]. Regarding fossil fuels, a price of 0.070 €/kWh has been considered. This value corresponds to the natural gas price in Europe during the first half of 2021 [76], [77].

In Table 7 the estimated savings per year of each installation are presented. All PV installations savings have been calculated considering the electricity price of the corresponding location indicated above. ST and PV-T installation savings in Rikshospitalet have been calculated considering the electricity price in Norway, since the thermal output would cover heating needs that the hospital currently covers by means of an electric boiler (subsection 4.1). In the case of the Cellini Clinic in Italy, there is no information available regarding the current energy source covering the DHW and heating needs, so the same scenario as in the case of Rikshospitalet is assumed. Therefore, the ST and PV-T installation savings in this case of study have been calculated considering the electricity price in Italy. Finally, for the Virgen del Rocío Hospital thermal needs are mainly hot DHW supply, which is currently covered by fossil fuels. Then, in this case the average price of natural gas has been considered for the ST and PV-T installations savings calculations.

Table 7. Estimated savings per year of each solar-based installation for an installation lifetime time of 25 years

Solar technology	Savings/year [€]		
	Rikshospitalet (Oslo)	Cellini Clinic (Turin)	Virgen del Rocío Hospital (Seville)
PV (e)	82,888	16,053	679,033
ST (th)	124,296	23,447	583,772
PV-T (e+th)	141,752	28,099	896,002

Then, the PBT is calculated as the time in years (n) when the net present cost (NPV) equals 0. In (5), the formula used for the NPV calculation is presented, were C0 is the total investment cost, Sn the estimated savings per year and d the market discount rate [78], [79]. The market discount rate is considered to be about 3%, for projects of 0-30 years lifetime [80].

$$NPV = C_0 - \sum_{n=1}^{n} \frac{S_n}{(1+d)^n} \quad (5)$$

From the calculations explained above, the PBT period for the PV installations in Oslo, Turin, and Seville is of 25, 5, and 7 years. The PBT period for the Cellini Clinic is slightly shorter than that of the Virgen del Rocío Hospital due to the higher grid-fed electricity price in the first case. In addition, PBT period in Oslo is about the life-time of the installation due to the low grid-fed electricity price in Norway and the low annual solar irradiance at this latitude. Regarding the ST and PV-T installations in Oslo, none of them present a PBT period lower than 25 years, again due to the low thermal output at this latitude and the low energy prices in Norway. In Turin, the situation is the opposite: due to the better climate conditions together with higher energy prices, the PBT period obtained of the ST and PV-T installations is of 9 and 8 years, respectively. Lastly, the PBT period estimated for ST and PV-T installations in Seville (if devoted to cover energy needs that are currently covered by natural gas) is of 25 and 13 years, respectively.

To finish, it is worth mentioning that given the current high variability of electricity and natural gas prices and their increasing tendency forecasted for the following years, estimated savings and PBT periods may be only considered as reference of a worst-case scenario. PBT periods for each hospital and location would be also strongly influenced by the current energy source/s that cover the hospital energy needs. What authors consider may serve as reference for on-roof solar-based installations for different climates (latitudes) are the obtained LCOE values in €/kWh presented in Figure 12.

4. CONCLUSION

Three different types of on-roof solar-based installations, photovoltaic (PV), solar thermal (ST), and photovoltaic-thermal (PV-T) are evaluated from the techno-economic point of view to cover the energy demand of hospitals in different climates: Rikshospitalet in Oslo (Norway), the Cellini Clinic in Turin (Italy) and Vírgen del Rocío Hospital in Seville (Spain). For the solar-based on-roof installations design and sizing optimization a novel in-house developed methodology is proposed. This methodology addresses hourly calculations over a full year analysing the optimum separation between rows of panels aiming, at the same time, the maximum possible energy generation per solar panel and the total energy generation over a year. Since these two parameters won't reach a maximum for the same installation capacity, a compromise solution will need to be reached. The useful annual energy output calculated for the locations of Oslo, Turin and Seville for the PV installations is 63.2, 95.3 and 161.2 kWh(e)/m^2, for the ST installations is 94.7, 139.2 and 211.9 kWh(th)/m^2 and for the PV-T installations 108.0, 166.8 and 267.2 kWh(e+th)/m^2, respectively. Depending on the hospital energy demand and roof area available for the solar installations, the percentage of the total energy demand covered over a year of the solar-based installations goes from about 2% for the coldest climate, Oslo, to about 15% in the warmest climate, Seville.

The installations costs are evaluated allowing to obtain the levelized cost of energy (LCOE) for each technology in different climates. LCOE values for on-roof installations obtained are of 0.028, 0.032, and 0.056 €/kWh for photovoltaic panels (PV), 0.051, 0.054 €/kWh and 0.096 for solar thermal (ST) panels, and 0.053, 0.066, and 0.128 €/kWh for photovoltaic-thermal (PV-T) panels, for the locations of Seville (latitude 37.4 N), Turin (latitude 45.1 N) and Oslo (latitude 59.9 N), respectively. PBT periods for each solar-based technology and location have been also estimated, concluding that given the current high variability of electricity and natural gas prices and their increasing tendency forecasted for the following years, estimated PBT periods may be only considered as reference of a worst-case scenario. Profitability of the different solar-based installations will vary depending on the solar technology output (electrical, thermal or both) and on the type of energy needs of the Hospital. Moreover, the price of the current energy source supplying the hospital energy needs is identified as the strongest influence parameter on the solar installation profitability. Results from this work aim to serve as reference for similar studies in a wide range of climates.

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