ENERGY ASSESSMENT OF FAÇADE-INTEGRATED SOLAR THERMAL COLLECTORS IN MULTI-FLOOR BUILDINGS

Paolo Bonato[1] and Roberto Fedrizzi[1]

[1]Eurac Research, Institute for Renewable Energy, Bolzano (Italy)

Abstract

The aim of this work is to assess the energy performance of solar thermal collectors integrated in the façade of residential and tertiary multi-story buildings. Here, the collected solar heat collected is exploited to cover a share of the space heating and hot water preparation thermal loads, replacing the use of a traditional fossil fuel-based generation system. The assessment is carried out with the use of dynamic energy simulations based on the TRNSYS software, where a thermal zone is appropriately characterized to model the modular unit composing the perimetral zones of the studied building types. The scope of the paper includes a parametrical analysis for three characteristic European climates (Mediterranean climate, Continental climate and Nordic climate), two specific water storage volumes and two facade designs. Based on the studied scenarios, it is concluded that façade-integrated solar thermal collectors applied to hotels, hospitals and dorms can well exploit the locally available solar irradiation and reach interesting solar yields and solar fractions, whereas office buildings show a poor matching at higher latitudes.

Keywords: BIST, solar thermal, dynamic simulations, TRNSYS.

1. Introduction

Over the last years, the integration of solar technologies into the buildings' envelope has gained traction, becoming a viable option for building designers and a business opportunity for the industry. Research projects and international networks such as IEA SHC Task 56 [1] and Cost Action 1403 [2] have studied the issue from the economical, technological and energy perspectives, with the aim to develop and promote solutions close to market. In the current panorama, the building-integrated photovoltaics sector counts for a wide range of products offered in a variety of installation typologies, shapes and colors, and the elaboration of the standard EN 50583 [3] was a significant step toward a progressive development of the industry. Conversely, the market penetration of constructive solutions integrating solar thermal collectors in the envelope remains scarce, even though the solution holds a great potential in applications that show a good matching between solar availability and heat demand, due to the high solar radiation-to-heat conversion efficiencies of thermal collectors.

In this sense, buildings such as hotels, dorms or long-term care wings of hospitals are characterized by high thermal loads that are largely connected to hot water preparation and thus do not show large seasonal variations. These applications could then represent a great opportunity for the use of solar thermal collectors. Tall multi-floor buildings, however, do not usually offer roof areas adequate for solar thermal installations with good load coverages, as the limited roof surface is often devoted to the installation of technical equipment such as air handling units, chimneys, antennas, dry coolers, façade cleaning equipment etc. On the contrary, facades offer plenty of available surfaces for solar installations, but in fact they are rarely exploited for this scope, even when the solar exposure is favorable and the external shading is negligible.

In literature, a few studies tackle the topic of the façade-integration of solar thermal collectors in multi-story buildings. Hegarty et al. explored the application of building-integrated solar thermal collectors in a number of building types, focusing however only on the hot water preparation thermal load and limiting the investigation to the climate of Dublin. In his study, Hegarty concludes that there is a case for façade integrated solar thermal collectors as a result of limited roof spaces, especially for high rise buildings with high hot water consumption [4]. Giovanardi investigated the integration of unglazed solar thermal collectors in the façade of a hotel and a multifamily residential building [5]. Sánchez-Barroso et al. studied the use of solar thermal

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collectors for hot water preparation in hospitals in the Spanish region, reporting very interesting payback time values (4.7 years) [6]. His study focused on roof installations, but the conclusions are very encouraging to explore other ways of integrating solar thermal collectors when roof surfaces are not available. In this context, the aim of this paper is to assess the energy performance of façade-integrated solar thermal collectors applied to energy-intensive multi-story buildings such as hotels, dorms and hospitals by quantifying the share of the thermal load (including both space heating and hot water preparation) that can be covered with solar thermal energy in a variety of climates. Additionally, the case of office buildings is considered for comparison purposes.

To reach this goal, thermal loads and solar heat production are estimated by numerical models developed with a dynamic energy simulation software (TRNSYS). Here, the most simple and modular units composing the perimetral zones of the studied building typologies (a hotel room, a dorm room, a long-term care wing of a hospital and an office cell) are characterized with literature values with concerns to infiltration, ventilation, hot water load etc. Annual energy simulations are performed for a range of European climates (Rome, Stuttgart and Stockholm) and relevant key performance indicators such as annual solar yield, solar fraction and annual useful energy demand are calculated to assess the performance of the technological solution.

In the next section, methodology and simulation models are described with focus on the energy system and the thermal zone, so to provide the reader with a better comprehension of the outcomes of the assessment. In section three, the key performance indicators are illustrated, and the numerical results of the energy simulations are reported and discussed. The paper concludes highlighting the main results with an outlook to future work.

2. Methodology and simulation model

The assessment of the facade-integrated solar thermal solution is carried out for four building typologies (hotel, hospital, dorm and office rooms) via annual energy simulations performed with the use of the software TRNSYS. In the simulation environment, a numerical model is developed to represent the thermal zone and the components of the energy system including solar thermal collectors, piping and a water storage.

More in detail, the thermal load is assessed considering the hot water preparation load and the space heating demand of the perimetral areas of a floor of the building, neglecting common areas and technical spaces. To further simplify the modelling approach and the computation load, it is assumed that the perimetral area of the floor is divided into multiple identical spaces (or rooms), which are taken as the modular elements of the building structure. The space heating load is then composed around the load of a single-room reference zone tested in the simulation software for different azimuthal orientations, considering the blueprint of the floor shown in Figure 2. The space heating water loop is connected to a floor-based central water storage and delivers to the rooms the amount of heating power that maintains the convective air temperature at the setpoint. The hot water preparation load is accounted as a heat withdrawal from the water storage.

Figure 1 shows a 3-dimensional view of the modelled thermal zone and Table 1 lists its main characteristics and relevant features.

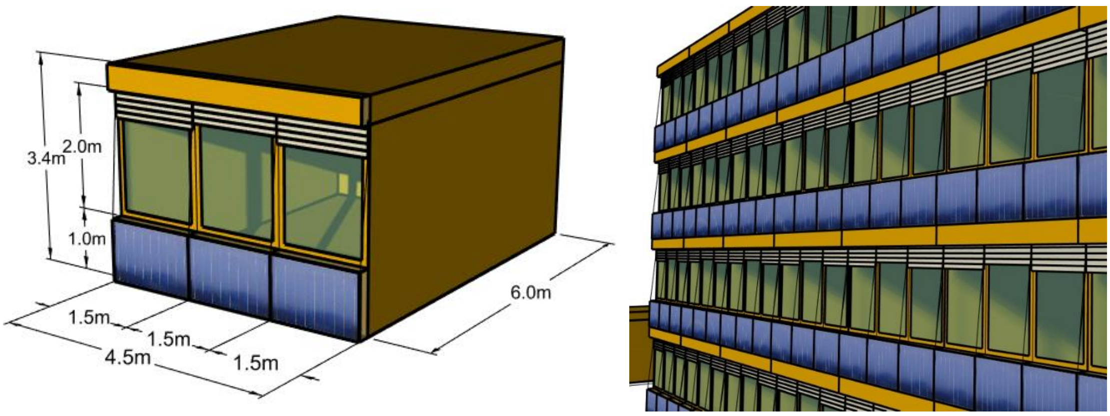

Fig. 1: 3D rendering of the thermal zone (left) and the building facade (right) – Window-to-wall ratio = 60%

Tab. 1: Thermal and optical properties of the external wall

Building assemblies			
g-value (glass)	Stockholm	0.63	
	Stuttgart	0.59	
	Rome	0.33	
U-value (glass)	Stockholm	0.81	W/(m²K)
	Stuttgart	1.29	W/(m²K)
	Rome	1.40	W/(m²K)
U-value (window frame)		1.18	W/(m²K)
U-value (opaque)		0.25	W/(m²K)
Window-to-wall ratio (incl. frame)		45 to 60	%

Tab. 2: Boundary conditions and characterization of the reference thermal zone

	Hotel room	**Hospital room**	**Dorm room**	**Office room**	
Geometry and occupancy					
Floor area	27				m²
Gross air volume	81				m³
Full-occupancy rate	2				p/room
Crowding index	0.07				p/m²
Ventilation and infiltrations					
Design ventilation rate (during occupancy)	11				L/(s·p)
Heat recovery efficiency [7]	70				%
Infiltration rate	0.15				1/h
Movable solar shading system					
Shading factor (when activated)	70				%
Beam radiation threshold for shadings activation	150				W/m²
Internal gains [7]					
Human presence – Latent heat gain	0.08				kg/(h·p)
Human presence – Sensible heat gain	70				W/p
Usage hours per day	16.0	24.0	17.0	11.0	h/day
Full occupancy hours per day	12.2	24.0	14.0	7.2	h/day
Day off per week	0	0	0	2	day/week
Appliances – peak power	8.0	4.0	8.0	7.0	W/m²
Appliances – standby consumption	0.8	0.4	0.8	0.7	W/m²
Artificial lighting – peak power	2.7	4.5	2.7	11.6	W/m²
Contemporaneity factor	70	80	80	80	%
Thermal demand					
Hot water demand (at 60°C) [7]	40	60	35	3	l/(day·p)
Tap water temperature [7]	10				°C
Space heating set point temperature	21				°C
Energy generation, storage and distribution					
Average efficiency of gas boiler	85				%
Insulation thickness of pipes (λ = 0.04 W/m/K)	3 (pipes), 15 (storage)				cm
Length of the pipes	109 (solar loop), 207 (heating loop)				m
Water content of the storage	40 to 70				l/m²

It is assumed that flat solar thermal collectors are installed into the lower opaque section of each of the three 1.5 m wide modules composing the façade of all rooms facing South. The solar collectors integrated in the facade of single rooms are connected in series whereas the circuits of different rooms are connected in parallel, as shown in Figure 2. The solar heat is delivered to a floor-based water storage and partly replaces the use of a back-up heat generation system (gas boiler) that is connected in parallel to the same storage. Two solar collector sizes are considered, thus leading to designs of the façade showing different window-to-wall ratios (WWR). Geometries and thermal properties of the solar thermal collectors are reported below in Table 3.

Tab. 3: Geometries and thermal properties of the flat solar thermal collectors

	WWR	Gross area (1x collector)	Aperture area (1x collector)	Gross area (per room)	Slope	Eta0	a1	a2	Back-Insulation
Size #1	45 %	2.25 m^2	2.00 m^2	6.75 m^2	90°	0.79	3.979	0.014	70 mm Rockwool
Size #2	60 %	1.50 m^2	1.34 m^2	4.50 m^2					

The simulation model features a thermal link between façade module and solar collector, meaning that the presence of the solar thermal collector influences the thermal load of the zone and vice-versa. It is assumed that the solar thermal collectors are installed on the South-façade of the building and that the external shading is negligible.

It is assumed that the reference floor has an overall area of about 500 m^2 and that the width-to-depth ratio is equal to 2:1, as illustrated in Figure 2. Table 4 reports relevant data on the geometry of the floor and on the solar thermal collectors' field.

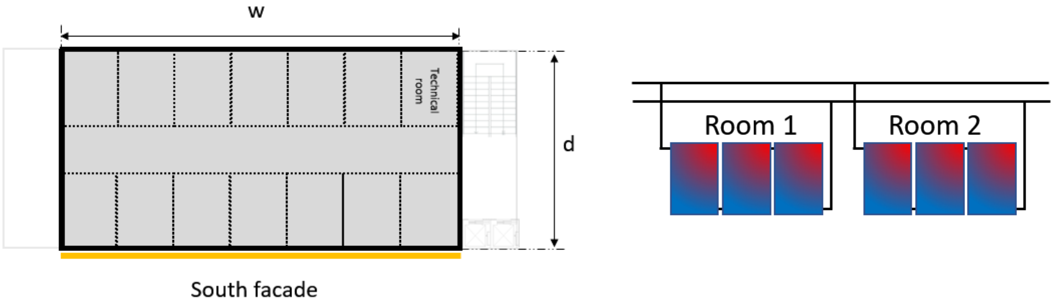

Fig. 2: Floor design (left) - top view, width (w) and depth (d) of the floor highlighted, Hydraulic connections (right)

Tab. 4: Geometry of the reference floor and the solar thermal collectors' field

	Solar collectors' area per floor	Solar collectors' area / Total façade area	South façade area per floor	Total façade area per floor	Floor area (w x d)	Rooms area / Floor area
WWR = 45%	47.3 m^2	15 %	107 m^2	321 m^2	496 m^2	71%
WWR = 60%	31.5 m^2	10 %				

To widen the scope of the paper and investigate the performance of the solution in a variety of contexts, the energy analysis is conducted for three representative European locations, that is Rome (Italy) for the Mediterranean climate, Stuttgart (Germany) for the Continental climate and Stockholm (Sweden) for the Nordic climate [8]. The weather dataset used in the energy simulations is generated using the database Meteonorm 7 and contains hourly values of meteorological parameters such as ambient air temperature, humidity and solar radiation for a one-year period. For comparison purposes, Figure 3 and Table 5 show a selection of annual meteorological parameters for the three locations.

Tab. 5: Annual meteorological data for the three locations (Rome, Stuttgart and Stockholm) – Global irradiation on the horizontal ($H_{0°}$), Global irradiation on a vertical South-facing surface ($H_{90°,S}$), Average ambient temperature ($T_{a,av}$) and Heating Degree Days (HDD)

		Rome	Stuttgart	Stockholm
$H_{0°}$	kWh/(m^2·y)	1637	1105	954
$H_{90°,S}$	kWh/(m^2·y)	1267	899	900
$T_{a,av}$	°C	15.8	9.9	7.8
$HDD_{12,20}$	Kd	1355	3220	3998

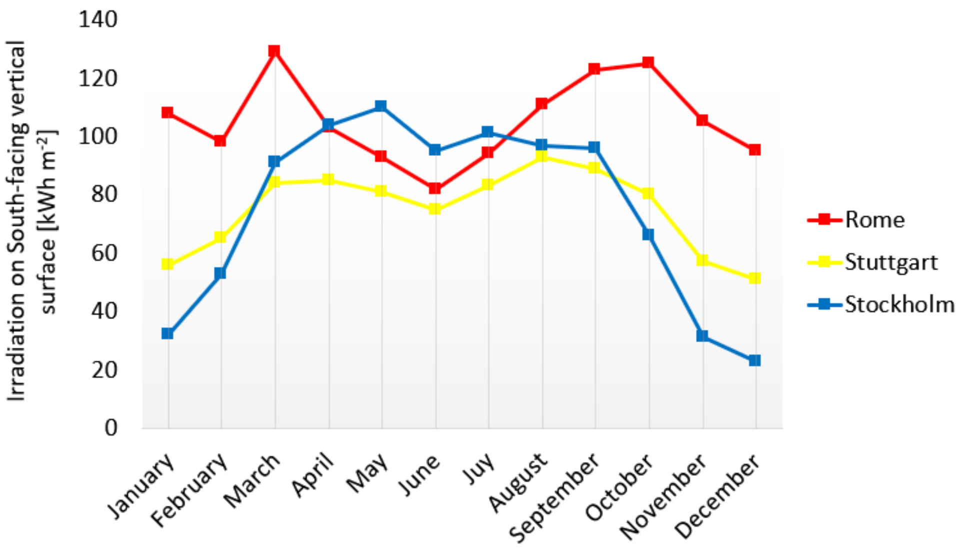

Fig. 3: Monthly irradiation on a vertical South-facing surface for the three locations (Rome in red, Stuttgart in yellow and Stockholm in blue)

Finally, a parameter that can significantly influence the energy performance of solar thermal systems is the size of the water tank, with larger volumes usually corresponding to better solar yields. To quantify this effect on the overall performances, two storage sizes are considered corresponding to 40 and 70 liters of water per square meter of solar thermal collectors' area. To summarize, Table 5 lists the parameters investigated in this study. Such factors are evaluated in a full-factorial combination, for a total of 48 different scenarios.

Tab. 5: List of the parameters considered in the study

Climate	Building type	WWR	Tank size
Rome Stuttgart Stockholm	Hotel Hospital Dorm Office	45% 60%	40 l/m^2 70 l/m^2

3. Results and discussion

The key performance indicators considered for the energy assessment are the annual solar yield, the solar fraction, the annual thermal load, the energy contributions to the water storage and the utility bill savings. All quantities are expressed per square meter of floor area unless stated otherwise. The results of the energy assessment are reported in Table 6 and discussed below.

- The annual solar yield is the solar energy harvested by the solar collectors over the course of one year per square meter of collector's gross area.
- The solar fraction is the share of thermal energy generated by the solar thermal collectors' field.
- The annual thermal load is the thermal energy for space heating and hot water preparation made available to users by the energy system over the course of one year.
- The annual energy contributions to the storage are the thermal energy inputs of back-up system and solar collectors' field to the water storage over the course of one year. Their sum is higher than the annual thermal load since storage and distribution heat losses are also accounted.
- The energy bill saving is the monetary saving achieved over the course of one year thanks to the solar thermal collectors. The saving is calculated against a set of baseline scenarios where the solar collectors are not implemented. The bill is calculated assuming an energy price of 0.10 euro/kWh for gas and 0.20 euro/kWh for electricity, and accounts for the consumption of auxiliaries (circulation pumps). Possible subsidies to renewable energy generation are not included.

Tab. 6: Results of the energy assessment for four building typologies (hotels, hospital, dorm and offices), three locations (Rome, Stuttgart and Stockholm), two window-to-wall ratios (45% and 60%) and two tank sizes (40 l/m² and 70 l/m²)

Scenario				**Energy assessment results**							
	Climate	WWR	Tank Size	Annual solar yield	Solar fraction	Space heating thermal load	Hot water prep. thermal load	Total thermal load	Heat generated by gas boiler to tank	Heat generated by solar field to tank	Annual energy bill saving
		%	l/m²	kWh/m²	%	kWh/m²	kWh/m²	kWh/m²	kWh/m²	kWh/m²	€/year
HOTEL	Rome	45	40	414	74%	6.5	31.1	37.6	12.8	36.2	1999
			70	436	78%	6.5	31.1	37.6	11.1	38.4	2096
		60	40	487	59%	7.5	31.1	38.6	20.7	28.6	1599
			70	520	63%	7.5	31.1	38.6	18.8	30.8	1713
	Stuttgart	45	40	282	40%	20.0	31.1	51.1	37.1	25.0	1386
			70	301	43%	20.0	31.1	51.1	35.6	26.9	1472
		60	40	322	30%	22.5	31.1	53.7	45.0	19.1	1072
			70	346	32%	22.5	31.1	53.7	43.6	20.8	1156
	Stockholm	45	40	259	34%	25.2	31.1	56.3	44.6	22.9	1261
			70	278	36%	25.2	31.1	56.3	43.2	24.7	1341
		60	40	304	26%	28.0	31.1	59.1	51.7	18.0	1004
			70	326	28%	28.0	31.1	59.1	50.4	19.5	1081
HOSPITAL	Rome	45	40	508	68%	4.2	53.4	57.6	22.4	45.7	2594
			70	533	71%	4.2	53.4	57.6	20.2	48.4	2725
		60	40	582	52%	5.2	53.4	58.6	33.4	35.3	2018
			70	608	54%	5.2	53.4	58.6	31.8	37.2	2112
	Stuttgart	45	40	339	38%	17.7	53.4	71.0	50.9	30.9	1750
			70	359	41%	17.7	53.4	71.1	49.1	33.0	1854
		60	40	382	28%	20.4	53.4	73.8	60.7	23.4	1336
			70	403	30%	20.4	53.4	73.8	59.4	24.9	1414
	Stockholm	45	40	321	34%	22.3	53.4	75.7	57.4	29.1	1651
			70	341	36%	22.3	53.4	75.7	55.7	31.1	1749
		60	40	365	26%	25.3	53.4	78.6	66.7	22.3	1276
			70	386	27%	25.3	53.4	78.7	65.4	23.8	1353
DORM	Rome	45	40	411	77%	4.8	31.1	36.0	11.1	36.0	1989
			70	433	80%	4.8	31.1	36.0	9.5	38.1	2082
		60	40	486	61%	5.8	31.1	37.0	19.0	28.5	1595
			70	519	65%	5.8	31.1	37.0	17.0	30.8	1711
	Stuttgart	45	40	282	42%	18.0	31.1	49.1	35.1	25.0	1382
			70	301	44%	18.0	31.1	49.1	33.6	26.9	1471
		60	40	322	31%	20.6	31.1	51.8	43.1	19.2	1073
			70	346	33%	20.6	31.1	51.8	41.7	20.8	1155
	Stockholm	45	40	259	35%	23.0	31.1	54.1	42.3	22.9	1260
			70	278	37%	23.0	31.1	54.1	41.0	24.7	1340
		60	40	304	27%	25.9	31.1	57.0	49.6	18.0	1003
			70	326	29%	25.9	31.1	57.0	48.2	19.6	1081
OFFICE	Rome	45	40	184	88%	2.6	1.9	4.5	1.5	14.5	682
			70	199	92%	2.6	1.9	4.5	1.0	15.9	712
		60	40	247	73%	3.5	1.9	5.4	3.5	12.9	627
			70	266	77%	3.5	1.9	5.4	2.8	14.1	663
	Stuttgart	45	40	139	37%	11.2	1.9	13.1	13.4	11.4	536
			70	155	41%	11.2	1.9	13.1	12.5	12.9	586
		60	40	165	25%	13.9	1.9	15.8	18.0	8.8	421
			70	181	28%	13.9	1.9	15.8	17.3	9.9	458
	Stockholm	45	40	117	25%	13.9	1.9	15.8	18.0	9.5	431
			70	129	27%	13.9	1.9	15.8	17.5	10.7	460
		60	40	137	17%	16.9	1.9	18.8	22.6	7.2	329
			70	152	18%	16.9	1.9	18.8	22.2	8.2	357

The energy assessment shows that building type and climate greatly impact on the thermal demand in terms of overall load and composition. Conversely, the size of the water storage has no influence, and the use of different window-to-wall ratios affects only the space heating demand with limited effects on the total thermal load As expected, higher space heating loads are found for higher window-to-wall ratios and colder climates, despite the use of progressively more insulating glazing at higher latitudes. The total thermal load increases with the latitude and is general significantly higher for hotels, dorms and hospitals. For these building types, the annual hot water preparation heat represents the largest share of the total load (especially in the climate of Rome), and ranges from 31.1 kWh/m^2 in hotels and dorms to 53.4 kWh/m^2 in hospitals. In offices, the hot water preparation load represents instead the lowest share of the thermal demand and accounts for only 1.9 kWh/m^2. As exemplification, Figure 4 shows the annual thermal load for a number of building typologies and climates.

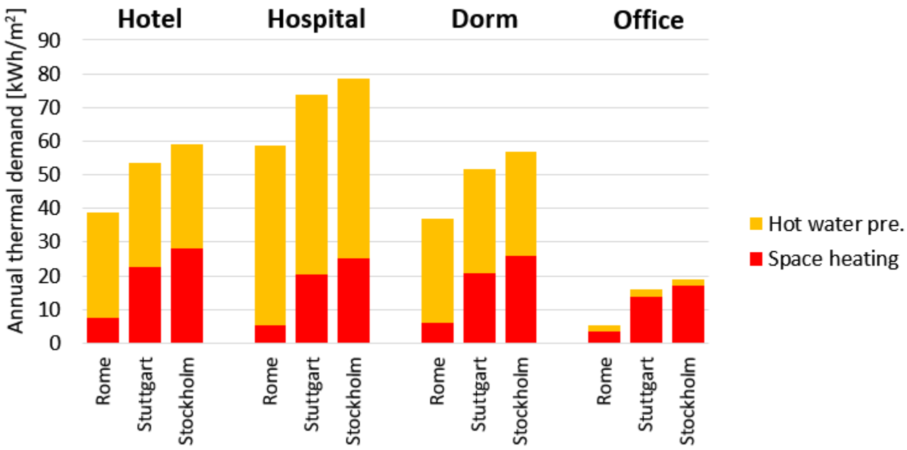

Fig. 4: Space heating and hot water preparation load for four building typologies (hotel, hospital, dorm, office) and three climates (Rome, Stuttgart, Stockholm) for WWR = 60%

Concerning the performance of the solar thermal field, it is observed that high solar coverage factors can be achieved in Rome (solar fractions ranging from 52% to 92%), whereas worse performance are reached in Stuttgart (from 25% to 44%) and Stockholm (from 17% to 37%). This is connected the availability of solar irradiation as already shown in Figure 3 and Table 5, and points to the obvious conclusion that solar systems perform better where the is abundance of solar resource. Looking at the solar yield figures, it is noticed that the building typology has a very high impact, and that even in harsher climates solar thermal collectors can have interesting solar yields in hotels, dorms and hospitals. This is because, as already seen, in these building types a large share of the thermal load is connected to hot water preparation, which shows only slight seasonal variations. It follows that in these localities it is still possible to generate valuable solar heat during summertime, when solar irradiation is not lacking and solar angles are not unfavorable as at lower latitudes. Office buildings, however, cannot exploit this opportunity, being most of their heat demand connected to space heating, which is required during wintertime.

The use of larger solar fields leads to higher solar fractions and a higher solar energy input to the storage. This growth is, however, less than proportional to the increase of the solar field area: increasing the collectors' surface of +50% (from case WWR = 60% to case WWR = 45%) leads to an increase of the solar fraction indicator ranging from 8% to 17% and of the solar field energy output from 13% to 32%, depending on climate and building typology. The reason is that larger solar fields can harvest more solar energy being the capture surface larger, but smaller solar fields are in fact exploited more intensively, as it can be clearly seen comparing the solar yield values. Given their lower energy output, smaller solar thermal systems tend indeed to work more hours with better working conditions due to the lower temperature level of the thermal system.

In all studied scenarios, the use of larger water storages enhances the solar performances of the energy system, with improvements that depend on building type and climate. For the same solar heating gain, higher water volumes allow to work with lower temperatures levels with resulting lower thermal losses in the solar pipe loop and thermal collectors. The total thermal losses through the storage mantle, however, might be higher due to the larger heat dispersing surface of the tank. Moreover, more solar heat can be stored before reaching the maximum temperature limits of the storage, thus promoting a better exploitation of the solar resource and reducing the number of stagnation hours. Furthermore, the higher thermal capacity also improves the capability of the system to store solar energy when available and meet the thermal demand when the solar irradiation levels are low or during nighttime. In the studied scenarios, it is observed that larger storages lead to higher solar fractions with improvements ranging from 1.3% to almost 5%, and better solar yields. More specifically, the largest increases of solar yield are achieved in climates with higher solar availability, for scenarios where the storage was already lower in size because of the smaller solar collectors field (that is WWR = 60%), and for specific building typologies (hotels, hospital, dorm).

As already discussed, the building typology has a substantial impact on the performances of the solar field. The best figures are achieved by the hospital building typology, with solar yields ranging between 321 kWh/m^2 and 608 kWh/m^2. The energy bill savings are also very significant, and range between 1276 euro/year and 2725 euro/year. Hotel and dorms show similar load profiles for both space heating and hot water preparation. The energy figures and the solar performances are also very close, with solar yields ranging from 259 kWh/m^2 to 520 kWh/m^2, and energy bill savings between 1003 euro/year and 2096 euro/year. Office buildings can also reach interesting solar coverages, with values in the same range as for the other building typologies. The solar yields, however, are much lower and range between 117 kWh/m^2 and 266 kWh/m^2, with energy bill savings ranging between 329 euro/year and 712 euro/year. For the office scenarios, a high number of stagnation hours is observed during summer in all climates but still the solar fraction figures remain low in Stuttgart and Stockholm. This is a clear indication that at higher latitudes the asynchrony of solar availability and thermal load throughout the year is a critical issue for solar thermal systems applied to office buildings. In the climate of Rome, instead, the solar irradiation on the South façade does not vary significantly from summer to winter, and thus a simple solution to increase solar yield and reduce overheating hours as well as the investment costs could be downsizing the solar field under 31.5 m^2 of solar collectors' area per floor, which is the lowest value tested in this study. It can be concluded that solar thermal applications such as the one proposed have a larger potential when applied to hospitals, hotels and dorms, whereas the application in office buildings should be carefully considered, especially at higher latitudes.

4. Conclusions

Based on the analyzed building and climate, one of the preliminary conclusion is that the integration of solar thermal systems into the façade of high rise buildings such as hotels, dorms and hospitals lead to interesting performances in terms of solar coverage of the thermal load and energy savings. The effects of climate and availability of solar radiation were quantified, and although the solar performances at higher latitudes are worse compared to the ones obtained in Southern locations, the possibility of covering high hot water load during summertime and mid-seasons represents a good opportunity for solar thermal systems. On the contrary, the thermal load of office buildings is primarily related to space heating and thus greatly vary during the year. This can be a critical issue at higher latitudes due to the low solar irradiation during the winter months. It was verified that larger solar fields allow to harvest solar energy, but that the increase is less proportional to the increment of solar field. For a +50% solar collectors' surface increase, an increment of the solar energy output between 13% and 32% was found depending on climate and building typology. Larger water storages consent to improve the solar yield and solar coverage, but such improvement tough not negligible remains limited to a maximum of +5% in the studied cases.

Future studies could investigate the economics of the proposed solutions, comparing estimated energy savings to the investment and maintenance costs of the solution over the lifetime of the façade. In addition, it could be interesting to compare the profitability of façade-integrated photovoltaics as alternative or complementary solution to a solar thermal field for the climates and building typologies considered in this study.

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