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Integrated solar thermal facade component for building energy retrofit

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To people I love

— True compassion is not just an emotional response but a firm commitment founded on reason...
— With the ever-growing impact of science on our lives, religion and spirituality have a greater role to play by reminding us of our humanity. There is no contradiction between the two.

Tenzin Gyatso, $14^{\text{ième}}$ Dalai Lama

This work represents a small step but also an important endeavor for me and it would not exist without the support of people who believe in me and my capacities.

I would like to thank Eurac research for funding my research activities and Prof. Paolo Baggio of University of Trento for the precious suggestions and support.

I thank all my team of EuracTec: Stefanino (for the precious moments spent on my balcony talking about the meaning of life), Paolo, Giulia, Laura and Francesco, Anna, Hannes, Marco, Roberto V., Dagmar, Gabriella and Matteo DB. They support me every day with being like they are and for sharing the same "lovely" office. The team of solar thermal guys, Chiara, Davide, Gabriele, Matteo D., the beautiful Patrizia and Roberto F., really helpful to me in understanding energy systems and Trnsys world.

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My best friend Roby who is a great person and makes me always smiling.

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My parents, Laura and Giorgio, and my brother, Luca, for being like they are, always great.

The Italian food for being simply the best.

Few months ago I have received an email that made me feel lucky to have around me people who want really take care of me, in bad and good times.

"Do something for the others, even if you are tired, even if you are unhappy
because only then you will start to see the beauty
only then you will start to sleep better
and only then you will be happy.
Don't run away
Have a good day".

So now, trying to understand where life will me bring and what will be the next in my own path, I am discovering how important these words have been for me and how much beautiful all the moments of my life are and how many possibilities could be if I look at the others with an open mind and an open heart. I really want to thank this special guy, Philippe, who is making me discover every day what life does mean,
it is suffering,
it is learning and improving,
it is trying always to do the best
and then
let it be.
I am enjoying life,
I am on my way.

Abstract

In the perspective of the "Net Zero Energy Buildings" as specified in the EPBP 2010/31/EU, herein a modular unglazed solar thermal facade component for facilitating the installation of active solar thermal facades has been conceived and designed to answer three considerations: (1) easily installable elements, offering high modularity to be sized for the specific needs of the buildings considered, (2) low-price unglazed technology, given by the industrial process already developed for the fridge evaporators, and (3) versatile modules to be used for both new buildings and for existing buildings for energy retrofitting.

The existing buildings stock offers a high-potential opportunity to improve the energy efficiency when using such a system. Indeed, the building envelope elements have a significant impact on energy consumptions and performances of the building, and this is a key aspect to consider during renovation.

Considering buildings integrating solar thermal (BIST) by the means of facade retrofitting of solar thermal collectors (STC) opens up new challenges for engineers. Facade usage, compared to the traditional roof installations, offers two interesting potentialities: (1) increased available surfaces, and (2) minimization of the unwanted overheating problem, that appears in summer, thanks to the vertical tilt (as the energy production is almost constant over the year). This allows sizing the STC according to the actual heat needs and avoids as much as possible energy fluxes mismatch.

The design methodology of such a modular component is the main contribution of the PhD work.
The challenges are tackled via a parametric approach. Dynamic simulation tools support the design choices for the energy systems of BIST and to optimize the interactions between the envelope and the STC with the criteria of reducing the overall energy consumption. This methodology is described and applied to the design of a modular prototype of an innovative facade component integrating unglazed STC.

We first analyze a variety of typologies of buildings as potential commercial targets of the facade component of unglazed STC integrated facade element. Both residential and non residential buildings are considered. The purpose of this analysis is to match the heat loads for properly sizing the facade elements for each typology. Benchmark models of buildings from the Department of Energy are used such as multifamily houses, hospitals, big and small hotels, schools, offices. These are simulated through EnergyPlus in three European locations (Stockholm, Zurich and Rome) in order to define the yearly heat loads for domestic hot water (DHW) and space heating (SH) needs.

Finally, the prototype is conceived and designed as a low-cost product to implement into facades with the criteria of optimizing the energy production. The unglazed STC is combined with a simple configuration of combisystem

in order to define some rule of thumbs through Trnsys. By the fact that the energy is produced at lower temperatures, if compared with glazed flat plate collectors, this technology is potential applicable to those buildings having the proper heat loads and the suitable system layout.

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Notation

absorbance absorbance coefficient of the absorber

A_{coll} collector absorber area

AEEG autorita per l'energia elettrica e il gas

BC boundary conditions

BIST building integrated solar thermal

Combisystem energy system for combined space heating and domestic hot water supply

DHW domestic hot water

DOE U.S. Department of Energy

F S2 flux through the surface S2

F S3 flux through the surface S3

F S5 flux through the surface S5

HE heat exchanger

HP heat pump

HVAC Heating, Ventilation and Air-Conditioning

Irr solar irradiation on the tilted surface of the collector

m_{coll} flow rate in the collector

Mtoe Million Tonnes of Oil Equivalent

NZEB net zero energy buildings

NR non-residential (buildings)

R residential (buildings)

SC space cooling

SH space heating

T_{amb} ambient temperature

Text external temperature

T_{out} outlet temperature from the collectors' field

T_{plate} average temperature of the collector absorber

T S2 temperature of surface S2

T S3 temperature of surface S3

T S5 temperature of surface S5

$\mathbf{T}_{stc}$ temperature of the solar thermal collector absorber

UST unglazed solar thermal

1
Introduction

Climate change, energy security and sustainable provision of heating and cooling are three major challenges that Europe has to face in the 21st century. This requires a multi-disciplinary approach and the coordination of efforts, which is the work of European Technology Platforms (ETPs) by bringing together industry and research to define short- and long-term research and technological development. The essential role of the renewable energies for heating and cooling is recognized as part of the European strategy towards the targets set out in the Renewable Energy Sources Directive ("RES Directive", 2009/28/EC). In the next future renewable energy technologies will become the main energy supply mean because (1) there is no alternative and (2) they are in line with an overall strategy of sustainable development.

Nearly 40% of all primary energy consumption in the EU is consumed in buildings for lighting, heating of space and domestic water, ventilation and air conditioning and for operating all aplliances used by building occupants. The European building sector has been identified as an area where important improvements in energy efficiency and huge reductions in energy consumption can be achieved. An increase of building energy performance can be an important instrument to reach the European targets by 2020. The recent recast of the EPBD 2010/31/EU has as objective the energy balance towards the so-called net zero energy buildings (NZEB) and stresses on the application of minimum energy requirements of existing buildings. As the art. 3 of the Directive states "*reduction of energy consumption and the use of energy from renewable sources in the buildings sector constitute important measures needed to reduce the Union's energy dependency and greenhouse gas emissions*".
The greatest potentiality of energy saving is in the existing building stock [1]. A renovation represents the high-potential opportunity to improve its energy

efficiency. It is the **building envelope elements** that have a significant impact on energy consumptions and performances of the building if they are retrofitted and replaced [2].

Solar technologies (ST) can play an important role in achieving the target of the energy balance towards NZEBs as the solar energy potential is huge in comparison with fossil energy sources: the amount of solar energy reaching the earth's surface in one hour is more than the world energy used in one year.
Within solar technologies, solar thermal ones transform solar radiation into useful heat or cooling with an efficiency about four times higher than the one of photovoltaic. 80% of the energy comsumption in buildings is used for hot water production in the residential buildings and space heating and cooling for both residential and non-residential sectors.
In the last years, the European solar thermal market has been growing fast even if it decreased by 10% in 2009 compared to 2008. The outlook for 2010 is quite uncertain as the economic crisis has still a negative impact on both public spending and incentive policies. The main markets are affected by lack of government incentive programmes and stagnation in the construction sector. Another important reason for a low diffusion of ST technology in the building field is the general lack of interest for this kind of technologies by designers and clients. According to the study of Weiss and Biermayr [3], solar thermal energy could supply 133 Mtoe (1552 TWh) of the final energy in the "Full R&D and Policy scenario" (RDP). The current applications of solar thermal technologies are:

- Domestic hot water production for the whole year (DHW);
- Space heating for colder season (SH);
- Space cooling for warmer season (SC);

In this perspective, buildings integrating solar thermal (BIST) become very interesting. The retrofitting into facades of solar thermal collectors (STC) opens up a new challenge for engineers. Indeed, facade usage increases the available surfaces and helps to avoid overheating in summer, thanks to the vertical tilt, as the energy production is almost constant over the year. This allows sizing the ST collectors according to the actual heat needs and avoiding as much as possible energy fluxes mismatch.

In this context, a new modular[1] unglazed solar thermal collector concept for facade integration in building energy retrofit actions has been developed.

The main contribution of this work is to show the potentiality, the development opportunities as well as the problems of merging two technologies, roll-bond technology and metal cladding system, into one component in order to answer both the engineering and architectural aspects related to the integration of solar thermal in the building envelope.

[1]modular in size.

A new active facade system was conceived and developed to answer three aspects: (1) easily installable modules, offering high modularity in order to be sized for the specific needs of the buildings considered, (2) low-price unglazed technology, given by the industrial process already developed for the fridge evaporators, and (3) versatile modules to be used for both new buildings and for existing buildings for energy retrofitting.

The existing European buildings stock offers a high-potential opportunity to improve the energy efficiency when using such a system. Indeed, the building envelope elements have a significant impact on energy consumptions and performances of the building, and this is a key aspect to consider during renovation.

The design methodology of such a modular unglazed solar thermal (UST) facade component is the main contribution of this work, in particular the parametric approach has a significant role. Dynamic simulation tools support the design choices for the energy systems of BIST and to optimize the interactions between the envelope and the STC with the criteria of reducing the overall energy consumption. This methodology is described and applied to the design of a prototype of an innovative facade component integrating unglazed solar thermal collectors.

The context analysis is provided in the second chapter, and the state of the art regarding technologies, cladding facade systems and existing technical and architectural problems is reported in the third one.

The real core of the thesis is presented in the fourth chapter. It described the possibility to merge two technologies, roll-bond technology and metal cladding system, into one product to answer both the engineering and architectural aspects related to the integration of solar thermal in the building envelope.

Once the proper cladding system is selected, a first configuration of prototype is proposed and studied to understand how this one interacts with the existing facade from the physical point of view. The concept design of the prototype and the methodological approach developed to address the final configuration design of the unglazed solar thermal/facade cladding system are described in details.

In the fifth chapter the results of the analysis of the heat loads for DHW and SH of some residential and non-residential buildings are presented in order to define the two reference buildings matching well the solar facade features, considering its modern and technological aspect and the actual building thermal loads.

The sixth chapter describes the results of the performance analysis of a building energy system including UST integrated in the envelope.

The best layout of the water heating system is defined through dynamic simulations in TRNSYS, considering different values of optimization variables as collector area and mass flow rate in the solar loop. The parametric analysis aims at evaluating the temperature of the water coming out from the collector field and how much percentage of hot water the solar system can provide to satisfy the demand in winter and in summer, while avoiding as much as possible overheating in summer-time.

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[2] Directive 2010/31/eu of 19 may 2010 on the energy performance of buildings. http://eur-lex.europa.eu/JOHtml.do?uri=OJ:L:2010:153:SOM:EN:HTML#_blank, 2010.

[3] Weiss W. and Biermay P. Potential of solar thermal in europe.

2

Analysis of the context

2.1 Abstract

Before going into details of the integration of solar thermal technology into existing buildings, this chapter analyses the reference frame through three aspects: (1) the building stock as the potential market for such an integration, (2) the energy consumptions and needs and (3) the existing solar thermal technologies.

Firstly, a study of the European statistic of the European residential and non-residential existing building stocks by construction period and typology.

Secondly, an analysis of energy requirements for domestic hot water and heating by building typology is carried out, on the bases of simulations. In the third part, the available solar thermal technologies for building applications and features of the facade system are described.

The study highlights the need for renovation. Moreover, it provides an understanding of the solar thermal potential of the European building stock according to their period of construction and the thermal energy demand for building typology. It is shown that the energy request could be totally or partially satisfied by using suitable and appropriate solar thermal technologies, implemented in the building facade. The application in facade is discussed in terms of added exposed surface and energy production potentialities.

2.2 Residential and non-residential existing EU building stocks

Renovation of the existing buildings represents a high-potential opportunity to reach high standard of energy efficiency of the building stock. It necessarily requires knowledge of the energy performance of the whole stock and its evolution. By knowing the age of construction and therefore the design and the characteristics of a building, it is possible to estimate roughly how much energy is consumed in and by a building, how much heating, cooling and ventilation energy is needed to have an internal comfort.

If new buildings can be constructed with high performance levels, older buildings, which represent the majority of the European building stock, are characterized by high energy consumption and are in need of renovation.

The starting point is the analysis of available statistics of the European building stock, by building typology, period of construction and energy use. This will provide us with a complete overview of the residential and non-residential sectors. How many buildings are there in Europe? How old are they? What are they used for? In general, answers are known to these questions for the residential stock, but much harder is to find for the non-residential case.

The European building sector has been identified as an area where important improvements in energy efficiency and huge reductions in energy consumption can be realised. An increase of building energy performance can be an important instrument to reach the European targets by 2020. The recent recast of the Directive on Energy Performance of Buildings (EPBD - 2010/31/EU) [3] has as objective the energy balance towards the so-called net zero energy buildings. A reduction of energy consumption and an increased use of energy from renewable sources play an important role "in promoting security of energy supply, technological developments and in creating opportunities for employment and regional development" [3]. In Art.1 and Art.7, the Directive stresses on the application of minimum energy performance requirements of existing buildings and on the renovation relating to the building envelope and technical systems. Indeed, building envelope elements have a significant impact on the energy consumption and performance of the building if they are retrofitted and replaced.

The most recent information about the energy performance of buildings in Europe are reported in the survey published in October 2011 by BPIE (Building Performance Institute Europe). The report has been done on the basis of available and recently updated data collected across all EU countries, including Norway ans Switzerland.
The useful floor space in the European 27 member states (EU-27), Norway and Switzerland is estimated around 250 thousand million m^2. The annual growth rate in the residential stock is of $+1\%$ even if in most countries there is a decrease in the rate of new constructions due to the current economical crisis in the building sector [4].

The non-residential building stock (NR) accounts for 25% of the total stock in EU and represents the most complex and heterogeneous sector compared

to the residential one (R). The main differences are in the usage, in how the energy is used and in the construction techniques.
Commercial buildings and offices form the largest portion of NR. They are followed by schools, hotels and restaurants, hospitals and sport facilities (see Figure 2.1).

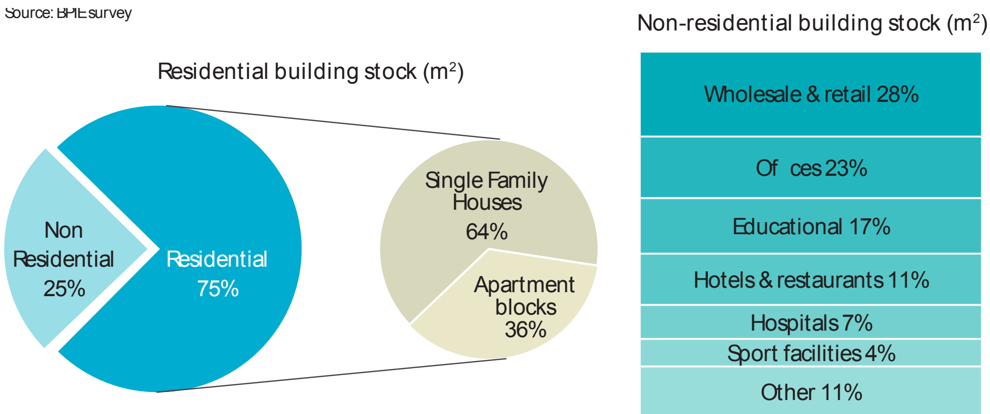


Figure 2.1: Residential and Non-Residential buildings In EU27, Norway and Switzerland - 2011 [4].

According to the investigation of Balaras [23], about 70% of the residential building stock is over 30 years old and about 35% is more than 50 years old. The age of existing buildings is an important factor also in relation to their energy consumption, given that most national building regulations regarding thermal insulation of building envelope were introduced after the energy crisis in the 1970s. In the past, building practices have not properly been addressed for an optimum use of energy in buildings and even less for the minimization of the environmental effects [23]. Moreover, the age of a building can also be correlated to the state of deterioration of building components and installations.

Figure 2.2 gives a breakdown of the European residential building stock by different construction periods. The pre-war residential buildings account for 20% to 39% of the total residential stock and the construction types are quite homogeneous. Dwellings built between World War II and the oil crisis account for 29% as European average. The construction characteristics are mixed, the buildings were in general insufficiently insulated and so the need for renovation is quite high. Between 1970 and 1990, the percentage of built buildings ranges from 21% to 27% of the total stock. In some countries as France, the Netherlands and Finland, the percentage is more than 35%. The dwellings built during this period are fairly well insulated, even if they need for renovation. Dwellings built after 1990 account for 8% to 22% with an average of 14%.

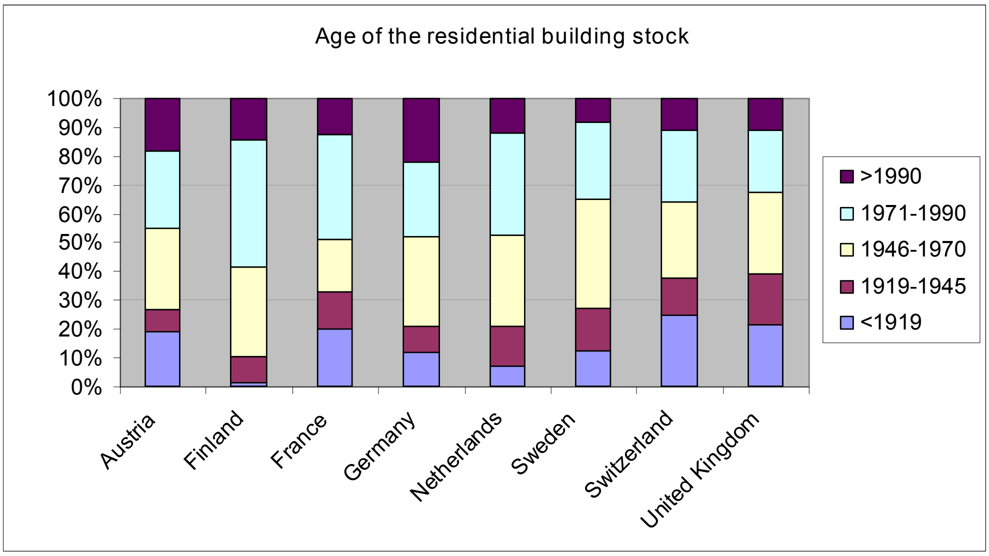


Figure 2.2: Age distribution of the housing stock in some European countries [15]

1. Austria: from ISIS database, data from 2003. These data are similar to the data in Statistics in the European Union 2004, data for 2002;
2. Finland: from Housing Statistics in the European Union 2004, data for 2002;
3. France: from Housing Statistics in the European Union 2004, data for 2002;
4. Germany: Data in m2 from IWU, based on micro census 1998 from Housing Statistics in the European Union 2004, data for 2002, (<1919: 14.6%; 1919-1944: 12.6%; 1945-1970: 47.2%; 1971-1990: 10.9%; 1980- 1990: 14.6%);
5. Netherlands: from Housing Statistics in the European Union 2004, data for 2002 and from KWR 2000;
6. Sweden: from Statistics Sweden (data for 2005). Differs a little from Housing Statistics in the European Union 2004, data 2003 (<1919: 12.4%; 1919-1944: 17.7%; 1945-1970: 21.2%; 1971-1990: 21.8%; >1990: 18.5%);
7. Switzerland: Data from BFS Wohnungszählung 2000;
8. United Kingdom: Data based on English House Condition Survey 2005. Data from Housing Statistics in the European Union 2004 give a slightly different share (<1919: 20.8%; 1919-1945: 17.7%; 1946-1970: 21.2%; 1971- 1980: 21.8%; 1980-1990: 18.5%).

The age of the non-residential building stock has been estimated within the EURIMA report [2], 64% of the stock at European level seems to be built before the oil crisis.This is confirmed by the BPIE survey as well.

Figure 2.3 shows a classification of the residential building stock in Italy by period of construction, concerning the national investigation of the ISTAT in 2001. The Italian building stock is characterized by a large presence of old buildings and a low renovation rate, according to the Italian partner of the TABULA project [6]. Some further considerations have been highlighted, as significant climatic differences among regions and different construction traditions (heavy construction in the South, wooden construction in the Alpine zones).

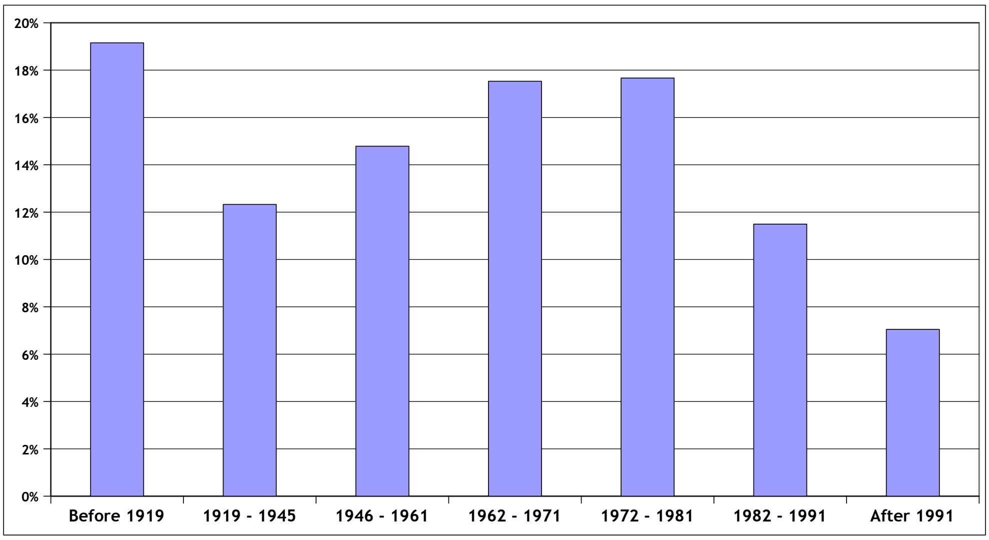


Figure 2.3: Residential buildings in Italy by period of construction - 2001 [5].

Both residential and non-residential buildings are objects of study but in general, there are much more official data available for the residential sector than for the non-residential sector. This is because 1) national statistical analyses have been carried out on a regular basis for the residential sector, 2) there is a lack of homogeneity of actors involved in the non-residential sector and 3) the non-residential building stock is smaller than the residential one [15].

The data on the residential sector come from the results of national investigation or housing surveys. In this way, the comparison of data between European countries can be difficult because of the use of different definitions, or different years of measure or different units. Data are sometimes given in number of buildings, number of dwellings, square meters of useful area. For example, building typologies can be represented differently in different statistics [15].

In Table 2.1, basic data about the European residential and non-residential building stocks are presented and Figure 2.4 shows the residential and non-residential floor areas per country.

	Population	Residential buildings			Non Residential buildings	
		m^2 U.A.	N° of dwellings	% m^2 U.A.	m^2 U.A.	N° of units
Austria	8 206 500	300×10^6	3 863 000	n.a.	n.a.	116 530
Finland	5 236 600	210×10^6	2 478 000	n.a.	n.a.	198 685
France	60 561 200	2135×10^6	25 800 000	72%	850×10^6	n.a.
Germany	82 500 800	3301×10^6	35 800 000	63%	$1\,926 \times 10^6$	n.a.
Netherlands	16 305 500	724×10^6	6 969 931	81%	166×10^6	224 000
Sweden	9 011 400	312×10^6	4 404 059	66%	158×10^6	n.a.
Switzerland	7 418 400	330×10^6	3 581 000	96%	151×10^6	84 615
United Kingdom	60 034 500	2236×10^6	26 200 000	71%	990×10^6	1 840 000
European stock	-	$9\,858 \times 10^6$	113 876 000	69%	$4\,354 \times 10^6$	n.a.

Table 2.1: Basic data on the residential and non-residential building stocks [15]

The total non-residential building stock of eight European countries analysed in the ERA-BUILD project [15] is 43% of the residential stock in terms of floor area. The percentages differ by country and account for 31% at European level (only cold and moderate climate zones were taken into account, except Switzerland).

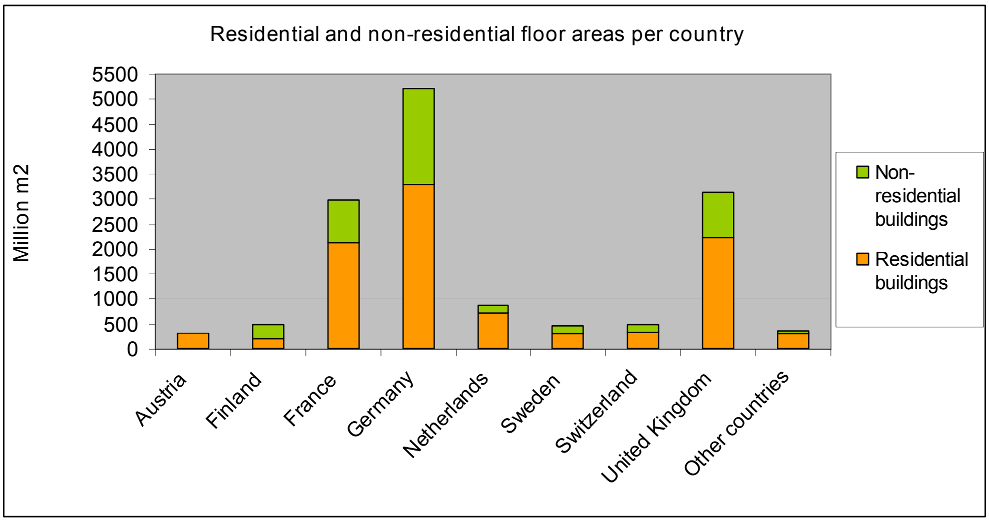


Figure 2.4: Residential and Non-Residential floor areas per some European countries [15].

The same considerations, about the lack of data concerning the non-residential, can be applied also for Italy, where the percentage of non-residential buildings, in term of number of units, is very low compared to the residential ones - see Figure 2.5.

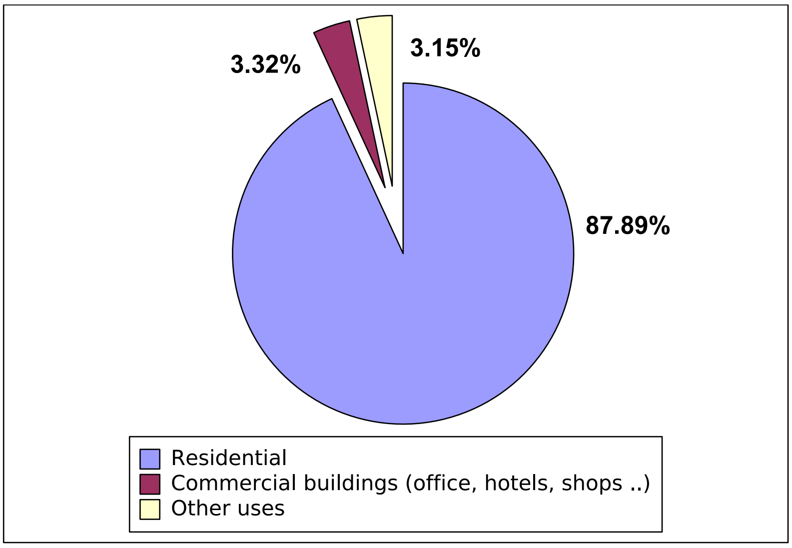


Figure 2.5: Building typology in Italy - percentages refer to 12.774.131 number of used total buildings - 2001 [5].

The research field of building stock analysis is still developing in Europe, since information is in most cases very limited. A European statistics to assess the amount of the building stock and its energy consumption is widely requested in order to allow a better comparison and monitoring of the building stock and the effect of European policies in the next future.

In answer to this need, Tabula project [6] has proposed to find a common definition to use as platform for mutual understanding of the building stock as well as their energy consumption and the measures to reduce it. Each participating country had to classify the residential buildings on the basis of age and size and to find examples of buildings for each class with a common methodology, in order to harmonize the information. The final aim of the Tabula project was to create a database containing all building models from all the countries.

The construction period is a valid parameter to individuate construction criteria (materials, construction principles, technical installations) used in the building and the standards of energy performance were in force in that period. Once the building stock is characterized, it is possible to investigate the energy saving potential and to vary a number of different parameters (insulation measures, energy system installation) and so it becomes much more easy to evaluate the potentiality of new technologies to apply in the building field.

In the end, the residential and non-residential buildings built between 1945 and 1970 should be the priority for an energy retrofit action, as this will yield the best energy usage improvement over all the building stock. Indeed, these buildings represent not only near one third of the stock, but they are inadequately thermally insulated and equipped with old installations. Many European projects have given their contribution to ideate and develop new technologies and materials suitable for new buildings. Whereas, these new technologies have not yet been adapted or optimized for the existing building stock. In Europe, there are just a few examples of application of prefabricated system for the energy retrofit, as the examples reported in the Annex 50 *Prefabricated Systems for Low Energy Renovation of Residential Buildings* [1] (see Figures 2.6(a), 2.6(b), 2.7(a) and 2.7(b)).

(a) Before the renovation of buildings (1959) - Graz (A)

(b) After the renovation by GAP-Solution and AEE INTEC, Austrian demonstration buildings for Annex 50 - Graz (A) [1]

Figure 2.6: Renovation of Dieselweg 4 - Graz (AT), 2008-2009

(a) Before the renovation of buildings (1959) - Graz (A)

(b) After the renovation with installation of ST collector on the south oriented facade - Graz (A) [13]

Figure 2.7: Renovation of Dieselweg - Graz (AT), 2008-2009. In the chapters 2.6.2 and 3.3.2 the same buildings are reported as examples of renovation with prefabricated facades.

In this perspective, the retrofitting of existing buildings represents the high-potential opportunity for the implementation of solar thermal in the envelope in order to produce hot water for domestic use and space heating. Building integrated solar thermal (BIST) becomes very interesting and the retrofitting into facades of solar thermal collectors (STC) opens up a new challenge for engineers, manufacturers and architects.

2.3 Heat requirements by building type in Europe

2.3.1 Breakdown on energy needs of buildings in EU

The European final energy consumption in the buildings sector for 2006 amounted to 467 Mtoe, that is the 40.9% of the total EU-25 final energy use, of which 294 Mtoe in dwellings (63%) and 173 Mtoe in services (37%) [12]. The EU countries with the highest final energy consumption in the residential and tertiary sectors are Germany, United Kingdom, France and Italy.

Figure 2.8 shows how the energy use is shared between the residential (R) and non-residential (NR) sectors, in particular the non-residential stock uses less than two fifth (37%) of the energy consumption used by the residential one.

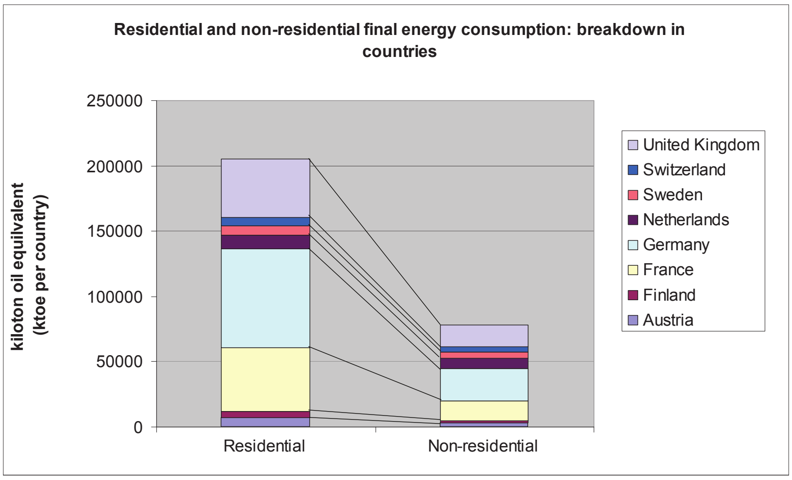
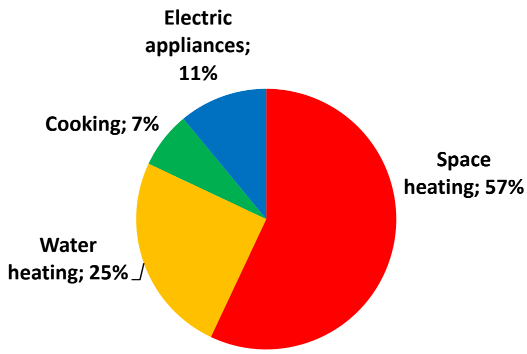


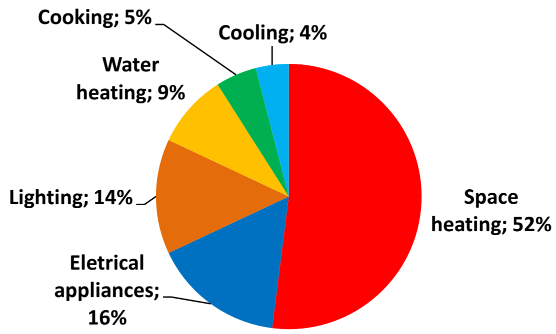
Figure 2.8: Total final energy consumption in residential and non-residential buildings: breakdown by country [15].

According to EuroACE report *Towards energy efficient buildings in Europe* [22] and to Balaras [10], most of the final energy consumption of residential and non-residential buildings stocks in the EU is used for space heating (see Figure 2.9(a) and Figure 2.9(b)). At the second place, in the residential sector water heating plays a major role (25%), while in the non-residential sector electricity and lighting accounts for 30%.

Looking at the specific situation of the NR stock, the energy consumptions of the main categories - offices, commercial buildings, hotels, schools and hospitals - are quite different among each others. Offices and commercial buildings' consumptions are growing strongly mainly due to the increase in AC demands and use of office electronic appliances (computers, printers). On the other hand, hotels show very high energy consumptions mostly due to heating and cooling of rooms, cooking and quite high sanitary hot water needs. Regarding



(a) Final energy consumption in the residential stock in EU: breakdown in end-use.



(b) Final energy consumption in the non-residential stock in EU: breakdown in end-use.

Figure 2.9: Final energy consumption for Residential and Non-Residential buildings in EU [15].

the hot water consumption, the demand depends on the hotel category, the number of beds and if the hotel does also offer the restaurant service to guests (see figure 2.10). Schools have usually the lowest energy consumption compared to the other NR buildings because of low AC needs - schools are closed during summer - and heating loads not so elevated due to high internal heat loads from occupants. Hospitals have the highest energy consumption due to high space heating, cooling and use of medical equipment which often runs 24 hours round.

According to the information collected by Santamouris and Moià-Pol on the Hellenic R and NR building stock [18], [17] and Ruan on the Japanese NR buildings [27], hospital is the building typology with the highest energy need, followed by hotel, office, commercial building and lastly school. The annual average total energy consumption in hospitals is 407 kWh/m^2, in hotels 273

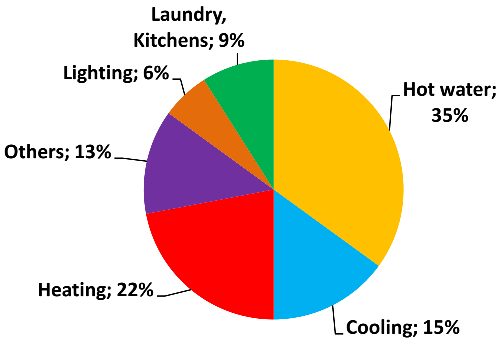


Figure 2.10: Energy consumption in a hotel in Greece [8].

kWh/m^2, in offices 187 kWh/m^2, in commercial buildings 152 kWh/m^2 and in schools $92kWh/m^2$. Focusing on the hotels located in the Mediterranean area, the average annual energy consumption is 215 kWh/m^2 in Italy, 287 kWh/m^2 in Spain, 280 kWh/m^2 in Greece and 420 kWh/m^2 in France [8]. In general, there are few available data about the yearly average value of the electrical and thermal energy use in residential and especially in non-residential buildings available for some EU countries (see [7], [11], [19] and [9]). Concerning DHW and space heating consumption values for NR buildings, it is quite rare to find official data at European level to take into consideration in order to get the daily and possibly hourly average heat demand of each kind of building. As already discussed in the previous section 2.1, up to date statistical publications, especially on the energy consumption of the non-residential building stock, are not available yet in Europe. In addition, there is no database of hourly energy load profiles relative to a reference building for each category, e.g. single and multi-family houses, offices, commercial buildings, hospitals, hotels, schools and sports centers, and for each European climate zone.

2.3.2 Benchmark models for residential and non-residential buildings

Regarding the residential stock, reference buildings - single-family and multi-family houses - were developed within IEA Task 26 Solar Combisystem, coordinated by W. Weiss, and heat loads were defined for the Zurich climate [26]. The load profile for DHW used within Task 26 was obtained with statistical methods in order to have fairly realistic conditions. The annual and monthly DHW energy demands were generated according to standards but, as the objective of the task 26 was the assessment of solar combisystems, the knowledge of the hourly load profiles of the building was actually necessary. So the reference buildings were simulated in TRNSYS in parallel with the combisystem in order to find the best match.

Concerning non-residential buildings, an analysis on the hourly heat demand is missing in Europe. It could be obtained through simulations. To do that, it is necessary to define building models for offices, commercial constructions, hotels, schools, etc. taking into account the stock and the thermal requirements for each end use of the building.

The benchmark models represent a common starting point which allows research results to be more easily compared [20].
The American Department of Energy (DOE) has developed a set of standard commercial building models for new and existing constructions to use for the evaluation of the energy performance of the whole-building on the basis of the American building stock. The DOE have selected 15 building types (among them the school in Figure 2.11), representing approximately 70% of the commercial building stock in U.S., with 3 ages (new, pre - 1980 and post - 1980 construction) and for 16 locations [20]. The building benchmarks are available for hourly energy simulations in Energy Plus version 2.2. The building models were developed taking into account many details, fairly realistic conditions and characteristics and some assumptions regarding thermal zoning, aspect ratio, orientation, numbers of floors, window surface, HVAC typologies, internal loads and equipment (see Table 2.2).
With running simulations in Energy Plus on each of the 15 building models, it is possible to get the annual, monthly and especially hourly energy use for DHW, heating and cooling for the 16 climate zones.

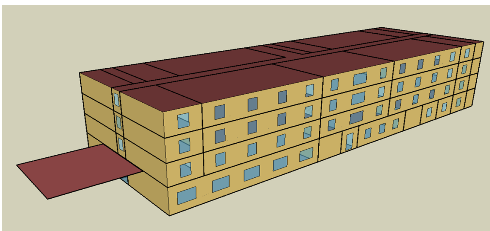


Figure 2.11: Low Category hotel DOE benchmark model [20].

Program	Form	Fabric	Equipment
Location Total floor area Schedules Plug and process loads Lighting densities Ventilation needs Occupancy	Number of floors Aspect ratio Window fraction Window locations Shading Floor height	Exterior walls Roof Windows Interior partition Internal mass	HVAC system types Component efficiency Control settings Lighting fixtures Lamp types Daylighting controls

Table 2.2: Input parameter categories used for Energy Plus [20]

A European building benchmark model to assess the energy consumption for each typology of building, residential and non-residential, is quite in demand in the research field. The building models allow a better comparison and monitoring of the building stock and the effect of European policies in the next future.

One of the objective of this work is to individualize the typology of buildings which get well together with a solar thermal technology implemented in the envelope.

Given the high-tech aspect that a solar application can have if installed especially in facade and given the heat load for DHW and space heating of several typologies of building, it is possible to define the proper buildings matching well from the energy and aesthetic standpoints.

In the chapter 5, an analysis on the DHW and space heating demand of DOE building models is described considering the results obtained with simulations run in Energy Pus.

2.4 Solar thermal technologies in building field

Solar thermal technologies use energy from the sun to heat water at useful temperature. This allows replacing other energy sources such as natural gas and electricity as means of providing hot water to the building.
Basically, solar thermal applications convert the short-wave solar radiation into long-wave heat radiation. This takes place in the absorber material, which must minimize reflection and maximize transmittance of the solar energy. For these reasons, selective absorber materials has been developed in dark colours in order to increase the conversion efficiency. The quality of a collector depends on the degree of efficiency, that is the ratio of the heat flow to the global radiation incident on the collector.

Solar coverage, expressed as a percentage, is an important parameter for the whole system, as it describes the contribution of the usable energy provided by the solar system on the total heating energy need of the building. The solar coverage or fraction is particularly influenced by the mismatch between the time of availability of solar radiation and the request of energy. One of the aims of solar thermal systems is to decouple the use of hot water from the availability of the solar radiation as much as possible. For this reason, a storage and a logical control have an important role in the energy system of the building.

The solar thermal systems have thus the task to convert solar radiation into heat and store it to make it available when it is required by the building users. The thermal energy is generally used in the building to heat or to cool indoor spaces and to heat the sanitary water.

2.4.1 Technical components

A solar thermal system consists of several components having the role to absorb, to carry and to store the heat. The most important part of a solar thermal system is the collector, whose role is to absorb the solar radiation and efficiently convert it to heat to transfer to the hot water system.
On the basis of the temperature at which the collector supplies the water and thus to its application, the solar thermal collectors can be divided in categories:

- Evacuated tubes collector
- Glazed flat plat collector
- Unglazed flat plat collector

Solar systems using liquids as transfer medium are more common. In order to avoid damages due to frost, the solar collector loop is usually separated from the actual water circuit and a water-glycol fluid is used. The mixture percentage is defined on the basis of the climate installation. Pipes are usually made of copper or polyethylene and connect collectors with the storage tanks.

Controls have an important function in the system since they firstly regulate the operation of the collector circuit, typically by controlling the pumps on the basis of the temperature difference between the sensors at the collectors and storage tanks. Secondly, the controls monitor the limit temperature in the solar circuit to avoid stagnation phenomenon.

2.4.2 Thermal performance

The thermal performance of a solar collector is determined trough a heat balance. This balance includes heat transfer terms such as convection, conduction and radiation. The simple model of heat balance of a solar thermal collector was defined by Hottel, Whillier and Bliss, the three pioneers of the solar field. As assumption of the HWB model of performance, everything is considered in "steady state" [14]. The performance of a solar collector depends on some parameters:

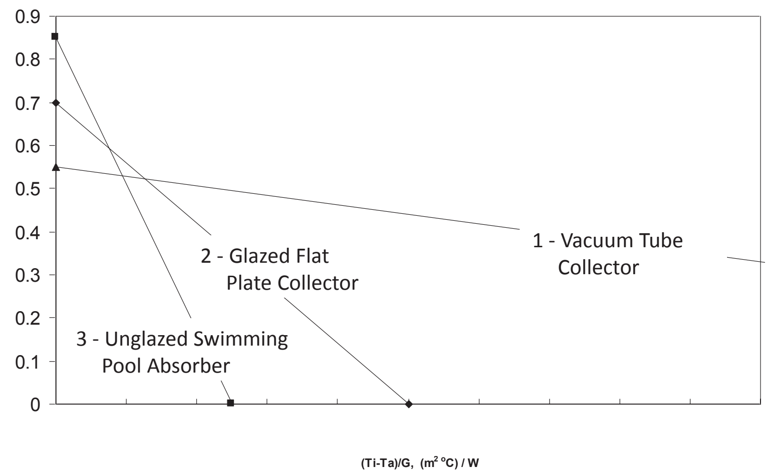
- optical and thermal performance noted by $(\tau\alpha)_e$ and U_L
- intensity of the solar radiation hitting on the surface
- surrounding environment temperature
- average temperature of the absorber

In Europe the fluid average temperature is used to characterize the solar collector performance and therefore the equation of the efficiency can be written as followed:

$$\eta = \frac{Q_u}{G_T \cdot A_c} \approx \left[F_R \cdot (\tau\alpha) - F_R \cdot U_L \cdot \frac{(T_m - T_{amb})}{G_T} \right], \tag{2.1}$$

where 1) F_R is the "heat removal factor" due to the fact that the fluid entering the collector is heated in the direction of the flow and so it goes out with a different temperature of the inlet fluid; 2) the efficiency is unit-less and the value ranges between 0 and 1; 3) the terms $F_R \cdot (\tau\alpha)$ and $F_R U_L$ are usually determined experimentally.

Solar thermal collector efficiencies generally fall within specific ranges (see figures 2.12(a) and 2.12(b)).



#	F_R ($)_e$	F_R U_L (W/m²°C)	
1	0.5 - 0.75	1 - 2	Depends on tube spacing
2	0.65 - 0.8	3 - 8	Depends on # of covers and absorber coating
3	0.8 - 0.95	10 - 20	Depends on wind speed

Figure 2.12: Solar collector performance depending in x-axis on $\frac{\overline{T}_m - \overline{T}_{amb}}{Gtot}$ [14]

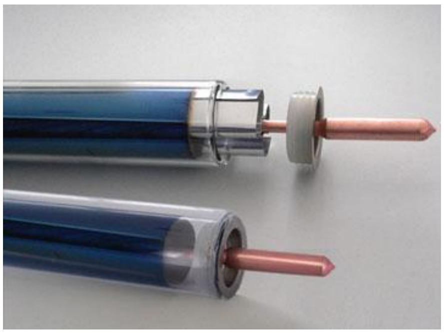
2.4.3 Solar thermal collector typologies

The **evacuated tube collectors** are composed of several rows of glass tubes containing the absorber suspended in the vacuum. The vacuum reduces convection and conduction heat losses to the outside and allows achieving the highest degree of efficiency and the highest operating temperatures. The efficiency of the evacuated tubes can be increased by using internal or external reflective surfaces. Generally, the absorbers inside each tube can be rotated in order to suit the solar radiation hitting the surface, making possible to reach good level of efficiency on horizontal, vertical or slopes in between. They are very efficient and can achieve very high temperatures.
There are two main types of evacuated tube collectors:

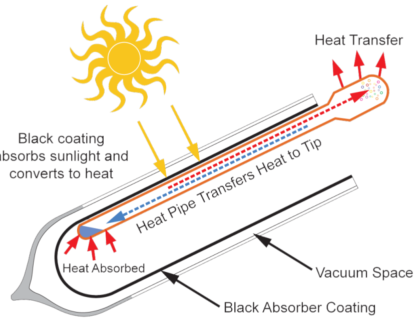
- **Direct-flow evacuated tube collector**: a direct-flow collector has two pipes that run down and back, inside the tube. One pipe is for inlet fluid and the other for outlet fluid. The tubes are not easily replaced in case of damage or problems, since the fluid flows into and out of each tube.

- **Heat-pipe evacuated tubes collectors**: a heat-pipe collector contains a metal absorber plate inside the vacuum and connected to the header pipe. Inside the heat pipe a quantity of liquid such as alcohol or purified water and additives. The vacuum enables the fluid to boil at lower temperatures. So when the heat pipe is heated by the sun, the vapour vaporizes and the vapour rises to the top of the heat pipe transferring

heat. At the condenser, the heat is lost and the vapour condenses to liquid and goes back to the bottom of the heat pipe to once again repeat the process.
Evacuated tubes are the preferred devices for applications needing high operating temperatures like industrial utilizations, space heating, solar cooling and domestic hot water provision.



(a) Particular of the heat-pipe tubes



(b) Structure of a heat pipe evacuated tubes collector

Figure 2.13: Evacuated tubes collectors [credit a: Irpem, credit b: Apricus.com]

Figure 2.14: Solar Decathlon 2007, Cincinnati University, Evacuated tubes on the south facade of the team's house [credit: Kaye Evans/Solar Decathlon]

The **flat plate collectors** are composed of an absorber plate, that is usually a metal sheet of high thermal conductivity with tubes integrated or attached. The surface can be covered with selective coating to maximize energy absorption and minimize radiant emission. Behind the absorber there is an insulation layer and above the absorber a glass cover,that lets sun light pass and produces a greenhouse effect avoiding heat losses.
In summer-time the overheating of the collector can damage the more sensible

Typical operating temperature	**70 - 130°C**
Degree of efficiency	**80-85%**
Typical applications	**DHW, space heating, solar cooling, industry**

Figure 2.15: Evacuated collector characteristics and applications [16]

materials and causes the stagnation phenomenon. When the antifreeze fluid reaches high temperatures, it loses its chemical characteristics and goes from the liquid to the gaseous state, but this process is not completely reversible. The gas generates some problems, including an increased pressure drop and a reduced heat transfer.

(a) Flat plate collectors installed on the roof

(b) Flat plate collectors implemented in facade

Figure 2.16: Flat plate collectors [credit a: Wagner & Co, credit b: Winkler Solar]

The **unglazed collectors** represent the simplest typology of solar thermal collector. These collectors are made of an absorber in metal, with an insulation on the backside, or in polymer. They are usually low cost collectors but they have high thermal losses due to the lack of the covering glazing. The metal absorber can reach higher temperature than the plastic ones thanks to the high thermal conductivity. As a result, unglazed collectors are commonly used for applications requiring delivering water at low temperatures, in swimming pools, low temperature space heating and to pre-heat the DHW.

As one more function, an unglazed collector can exchange heat through convective coupling to the air and through radiative coupling with the sky. During summer nights, it can reject heat accumulated during the day in the building and therefore to cool the indoor spaces. In winter, it can exchange heat through diffuse light even under a cloudy sky.

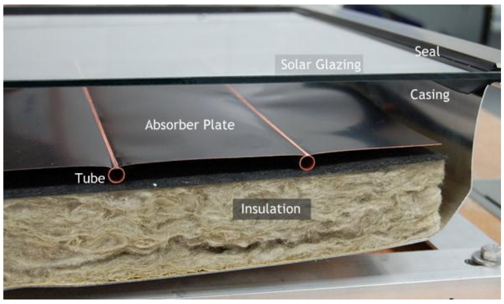


Figure 2.17: Particular of a glazed flat plate collector [credit: alliedsolar.ie]

Typical operating temperature	**60 - 90°C**
Degree of efficiency	**65-70%**
Typical applications	**DHW, space heating, solar cooling**

Figure 2.18: Glazed flat plate collector characteristics and applications [16]

(a) Unglazed collectors installed on the roof of the swimming pool in Brebbia (IT)

(b) Unglazed collector conceived for implementation in facade

Figure 2.19: Unglazed metal collectors [credit a: Energie Solaire, credit b: Atmova]

Typical operating temperature	**30 - 40°C**
Degree of efficiency	**40%**
Typical applications	**pool heating, DHW pre-heating, space heating**

Figure 2.20: Unglazed flat plate collector characteristics and applications [16]

2.5 Facade system features

2.5.1 Facade as key-element

When looking at a building, the first thing catching the attention is the facade. The facade is the key-element of a building, as it influences the space around the building and has impact also on the interior. In architecture, the facade of a building is often the most important from the design standpoint, as it sets the tone for the rest of the building. From a technical point of view, the facade is also a part of the building envelope, which is the separation between the interior and the exterior environments of the building. The facade has to deal with tasks as view, lighting, ventilation, user thermal comfort, some building services and possibly load-bearing [25].

(a) Arab World Institute, Paris (F), Arch. Jean Nouvel, 1981-1987.

(b) Distinguishing details of the moving geometric motif.

Figure 2.21: Example of facade: Arab World Institute (IMA), Paris (F)

Designing a facade is a process of communication from the architectural standpoint. In this sense, the design process of a building might consider the facade planning as integral part with a constant feedback on the overall design and the definition of element's functionalities. The design must take into account the climate of the location, the use typology of the building as well as the energy demand and finally the urban context in which the building is placed.

Figures 2.21(a), 2.21(b), 2.22(a) and 2.22(b) are two examples of facades having the target of communicating outside the purposes of the building.
The Arab World Institute(IMA) in Paris (figures 2.21(a) and 2.21(b)) symbolizes the aim to connect culturally France and the Arabic world. The South facade takes up the historical topics of the Arabic geography with moving geometric motifs, which are actually 240 motor-controlled apertures, opening and closing every hour. They act in order to control the light entering the building and therefore to create an effect often used in the Islamic architecture.

(a) University Library, Cottbus (D), Arch. Herzog and De Meuron, 1993-2005.

(b) Detail of the facade.

Figure 2.22: Example of facade: University Library, Cottbus (D)

The Technical University library in Cottbus (D) (figures 2.22(a) and 2.22(b)) has a double-skin facade of glass, printed with dots, alphabet letters and texts in several languages. As the building is not just a library but a multifunctional center, the facade should show the transformation of text into image.

2.6 Facade requirements

2.6.1 Legislative framework for technical assessment

In Europe there are statutory instruments, directives and standards of special interest to facade designers in order to address their planning with optimized approach and method. The Regulation **305/2011**, replacing the directive 89/106/CEE, defines the essential requirements that any building construction product has to satisfy to be placed on the market for an economically reasonable working life. Such requirements are: 1) mechanical strength and stability, 2) safety in the event of fire, 3) hygiene, health and the environment, 4) safety in use, 5) protection against noise and 6) energy saving and heat retention. The construction products, complying with the standards, are eligible to bear the "CEE" marking.

Concerning the construction systems, the **ETAG** reference guidelines set out the performance aspects to be examined to satisfy some requirements and verification methods of the performance. ETAG023 and ETAG025 are for example guidelines with regard to the technical approval for prefabricated building units and metal frame kits respectively.

Furthermore, support standards describe how to carry out testes on the systems.

Facade technical requirements

The facade is an element separating and filtering building environments – outdoor and indoor ones –, the nature and the interior space occupied by people. The external conditions as solar irradiation, temperature, humidity, precipitation and wind depend on the location and they strongly influence the design of the building and therefore of the facade. Whereas, the indoor conditions' requirements are defined by the comfort level necessary to reach and they are decisive during the design phase. The indoor comfort requirements also determine the energy demand of the building, the thermal and electrical needs. Generally, the facade has to provide protection and regulation functions in order to achieve an acceptable indoor thermal comfort (see Figure 2.23). The facade and in general the whole building envelope have to reduce the fluctuations of the external conditions. For example, the sun radiation reaching the wall surface leads to an energy gain inside the room. Part of this energy is absorbed by the wall material and transmitted by conduction. Another part is stored in the material on the basis of its heat capacity. The heat is afterwards transmitted to the room by radiation with a certain time-lag, depending on the thermal conductivity of the material. An energy-efficient envelope should guarantee that the indoor conditions are maintained over the whole year, mainly with maximizing the passive capacity of the envelope.

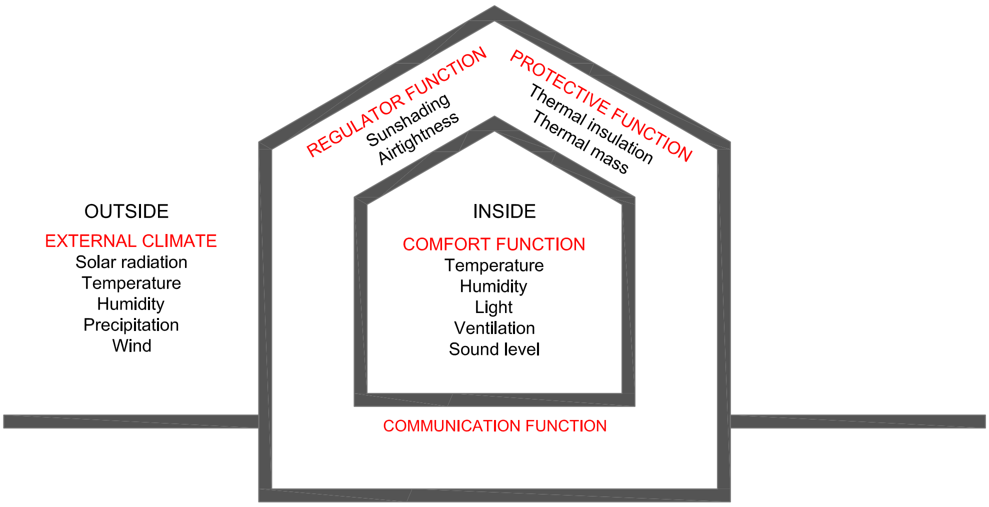


Figure 2.23: Conditions and requirements of a facade [drawn by Arch. G.Paoletti].

A facade is also part of the building structure and so there are also engineering requirements to take into consideration during the design stage. Temperature, humidity and pressure differentials cause mechanical loads on the wall structure, on the materials of the facade and on construction details. Permanents actions, vibrations, dynamic loads, shocks and self-weight of the material, which the facade is made of, are usually transferred into the different components of the supporting structures, to the columns and to the beams.

To summarising, a facade must answer functional, performance (structural and thermal) and expression requirements, as already suggested by some authors [24] and [21].

2.6.2 Method of construction: the modular approach

In the renovation process of a building, the modular approach could be an interesting option especially for envelope components. The facades can be made from prefabricated components, which are assembled in the factory under controlled and industrial conditions, with a high degree of automation and high level of accuracy. Careful design and assembly are necessary in order to avoid mistakes that can not be easily corrected in the next phase. This should guarantee a high standard quality of the prefabricated components, even if it requires more plan time and experienced designers and engineers. Moreover, interactions among elements as well as joining facade elements must be correctly designed because they represent typical weak spots of this system. Once assembled, the construction process in the site is quicker and few companies are involved, making possible reducing costs and whole times of completion.

Figure 2.24: Mounting procedure of the prefabricated modules for facade, renovation of Dieselweg 4 - Graz (AT), 2008-2009 [source: AEE INTEC].

2.6.3 Active elements integrated into facade

In the last 30 years, some new ideas of facade technology have been developed and some concepts from the modular facade - integrating more components - to the multipurpose facade - intelligent facade for all seasons - have been spreading [24]. From a construction point of view, the integration of many components directly into the facade is advantageous during industrial manufacturing process with a following installation on the site because it reduce construction times and costs. Technical equipment with the function of heating, cooling, ventilation as well as light-directing, shading, or elements integrating artificial lighting and even solar panels, both photovoltaic and thermal, can all be integrated in facade in the production phase [24]. In this sense, the prefabricated facades lend themselves to host new technical equipment in their structure and in particular to integrate solar thermal collectors.

In the European context, there are some examples of building renovation with prefabricated and modular elements integrating active elements and service distribution systems for heating, cooling and ventilation. The IEA Annex 50, concerning prefabricated renewal of buildings, has as objectives the development and the presentation of some case studies of innovative building renovation based on 1) prefabricated systems integrating HVAC, photovoltaic and solar thermal systems and 2) highly insulated envelopes with integrated distribution systems for ventilation, heating and cooling [1]. A practical example of case study is the renovation of the building envelope of "Dieselweg" residential area in Graz (Austria). On the existing walls, prefabricated modules were added and solar thermal collectors were integrated in the south-west facade of one of the buildings (see Figure 2.24).

2.6.4 Facade as surface available for solar thermal implementations

The answer, when asking people where they would install a solar thermal collector, will usually be on the roof. Indeed, the social understanding of solar technologies considers the roof as the natural location for them in order to minimize the aesthetic disturbance and to optimize the energy efficiency by tilted mounting of the collector. The ST systems are usually placed on the roofs and sized to cover at most the DHW demand of the building in order to avoid overproduction and overheating in the collectors in the summer season. The fluid temperatures inside the collector can reach high values causing damage the plastic components of glazed flat plate and evacuated tube collectors, whereas there is no problem for unglazed collectors. It is also important to highlight that in the last few years the European policies mean to improve the production of energy for building needs by solar technologies. This lets foreseen that there will be an increasing market demand of ST systems in the next years.
In this framework, facades provide further potential envelope surfaces for ST collectors implementation. Although the amount of incidence solar radiation on the vertical surface is lower than that on the tilted surface, the mounting in facade allows avoiding overheating in the collectors during the summer season.

In Europe the annual solar energy production of a solar thermal collector placed in a south vertical surface is almost constant, even if it is reduced by about 30% compared to optimal slope (see Figure 2.26, Figure 2.27 and Figure 2.28). More precisely, the reduction percentage of energy production is about 26%, 30% ans 35% less for Stockholm, Zurich and Rome respectively. As seen

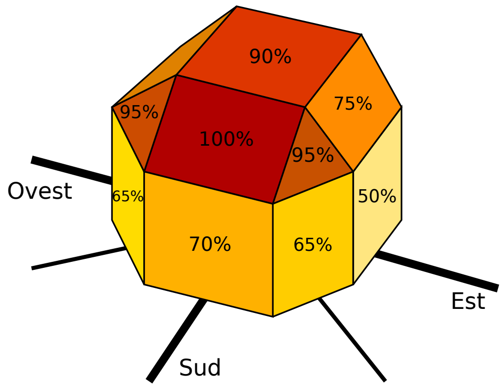


Figure 2.25: How the orientation affects STC installation in Europe.

in the figures 2.26, 2.27 and 2.28, the energy production profiles of a tilted slope and a vertical surface shows firstly a more constant trend for a south orientated facade, secondly only (optimal tilt and vertical south) two peaks in correspondence of spring and summer. The two profiles differ mainly in the energy production during summer-time, when the heat is not requested. This also avoids overheating of the ST collectors [26]. This makes easy the sizing of the energy system, according to the actual heat demands and to the available solar radiation and avoiding as much as possible energy fluxes mismatch. In case of a combisystem, the DHW need is more or less constant during the whole year, whereas the space heating demand depends on the locale climate and requires most of the energy in the winter season, when the solar irradiation is lowest.
When the ST collectors are mounted in vertical, they are less sensitive to the weather conditions and the powder, the rain and the snow do not cause damage as in the case of tilted mounting.

The example of facades implementing solar thermal collectors in a new construction in Vorarlberg (A) (Figure 2.29) shows a great sense in matching well colours, materials and frames.

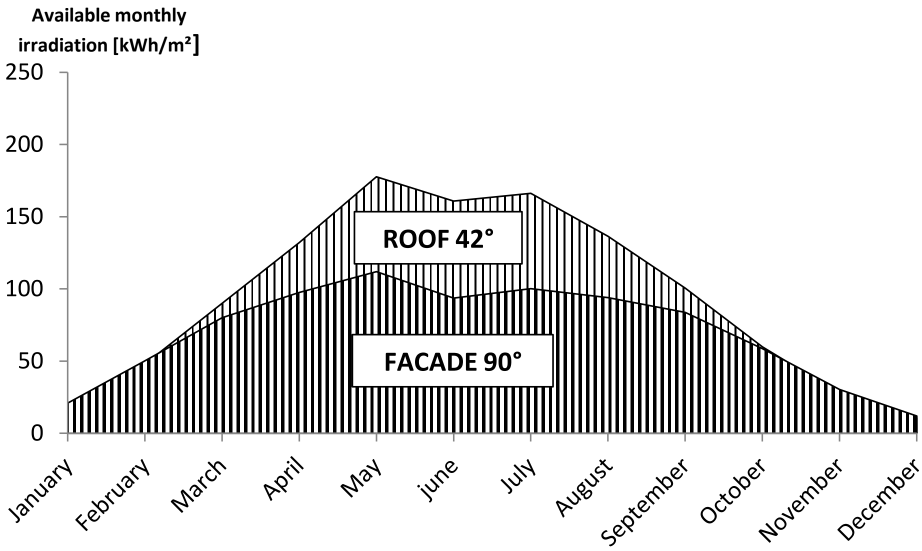


Figure 2.26: Comparison of the monthly sun radiation available on a 42° south exposed tilted surface vs. a vertical south exposed surface in Stockholm, Sweden 59°19' latitude). Data elaborated on monthly database of PVGIS.

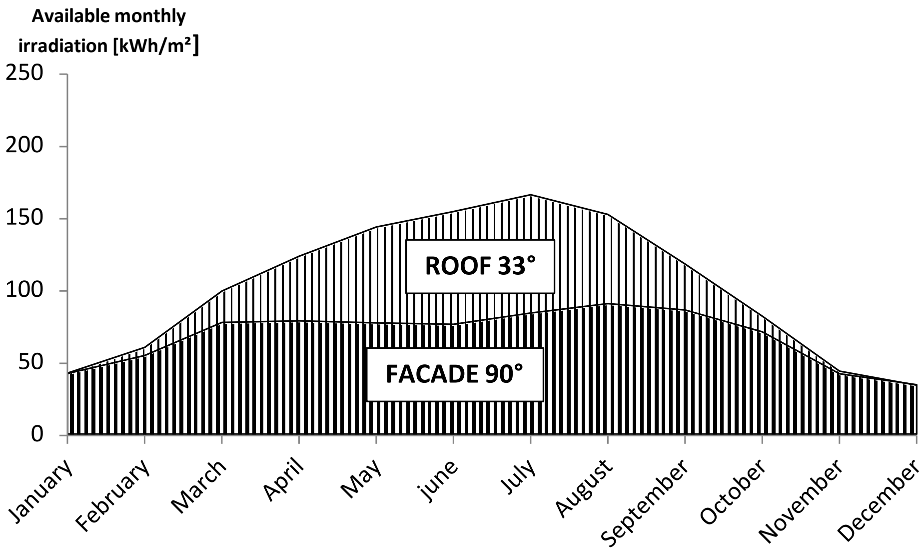


Figure 2.27: Comparison of the monthly sun radiation available on a 33° south exposed tilted surface vs. a vertical south exposed surface in Zurich, Switzerland 47°22' latitude). Data elaborated on monthly database of PVGIS.

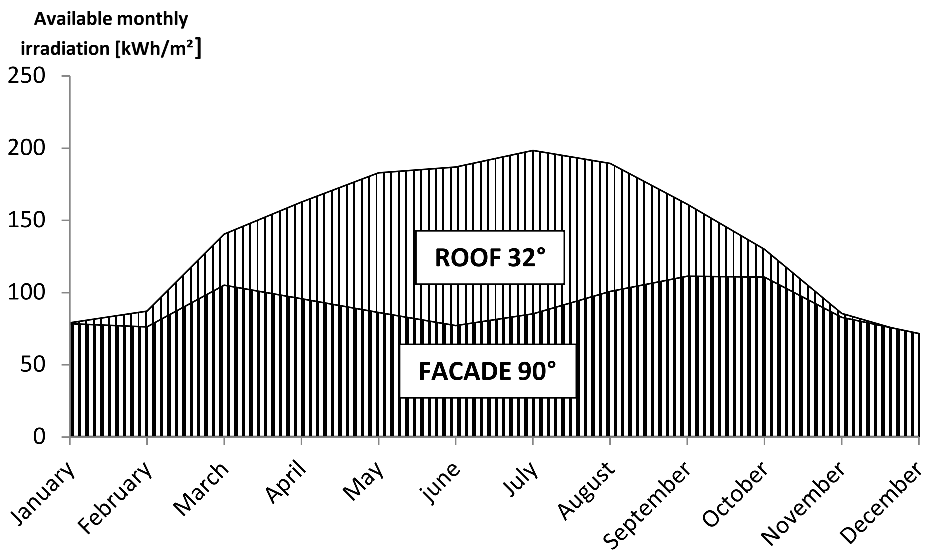


Figure 2.28: Comparison of the monthly sun radiation available on a 32° south exposed tilted surface vs. a vertical south exposed surface in Rome, Italy 41°53' latitude). Data elaborated on monthly database of PVGIS.

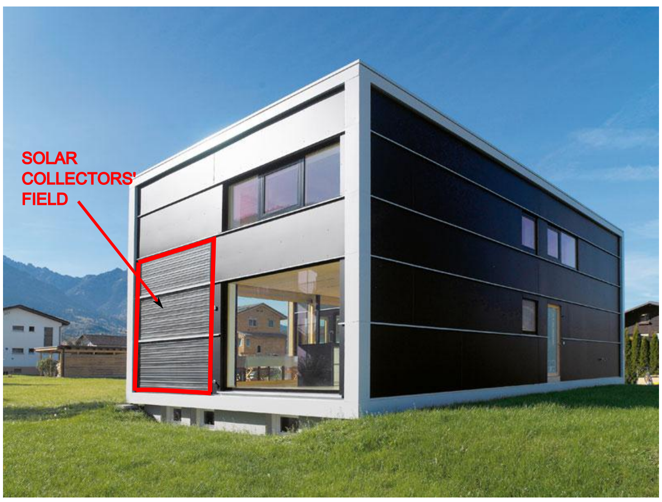


Figure 2.29: example of ST collectors integrated in facade, single family house, Nenzing (A), AKS Doma [credits: aksdoma.com]

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The Information collected in this chapter are based on a literature review using scientific literature, national and international reports and databases.

3
State of the art

3.1 Abstract

This chapter presents firstly an overview of the most advanced and innovative solar thermal technologies available on the European market and of the solar absorber prototypes developed for facade application.

Two examples of building renovation are reported to show how solar thermal can be integrated into building facades.

The analysis of the state of the art reveals the limits and barriers of the existing products related to the envelope integrability to answer both thermal energy productions and architectural issues.

In that respect, the roll-bond absorber technology is investigated separately as a promising technical solution for our interest. On an other aspect, metal cladding facade coverage is presented as a technique to answer the aesthetic/architectural issue.

The next chapter, will detail the main contribution of this thesis which studies the possibility to merge the two technologies into one product to answer both the engineering and architectural aspects.

3.2 Solar thermal technologies for facade application

Few companies in Europe proposes solar thermal collectors to implement in facade, but this technology is still largely underexploited in building field. Most products are conceived just as technical elements to be added on the roof or in the facade rather than to be integrated into the envelope, because it seems to be the less complex approach. Moreover, they are perceived by designers and users as an architectural unattractive solution. Nevertheless, they can be integrated in the opaque or transparent envelope, as mobile or fixed element, as single element or part of a multi-layered structure. To be integrated in the envelope, solar thermal collectors must satisfy some structural and aesthetic requirements in addition to ensure the same standard functions of the replaced element/s.

3.2.1 ST products available on the EU market

This section provides an overview of some innovative solar thermal products available on the EU market, mostly for facade applications. The technical specification of each product are described in a synthetic way on the basis of available manufacturer data. A summary of the specification sheets are given in the same format conceived for the guidelines for architects and manufacturers elaborated in the subtask A of SHC IEA Task 41 with their integrability potential [2].

Solar thermal window

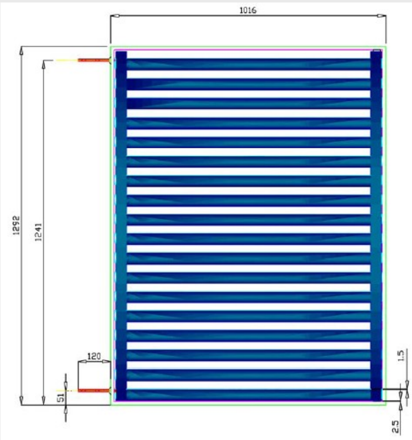
RobinSun Solar Thermal Glass, Robin Sun

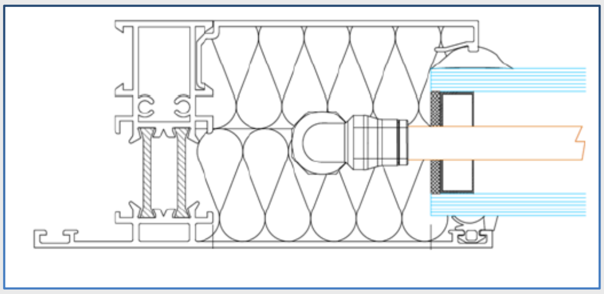
Rue fossé des tailleurs, 2 – 67000 Strasbourg, France
robinsun@robinsun.com
http://www.robinsun.com

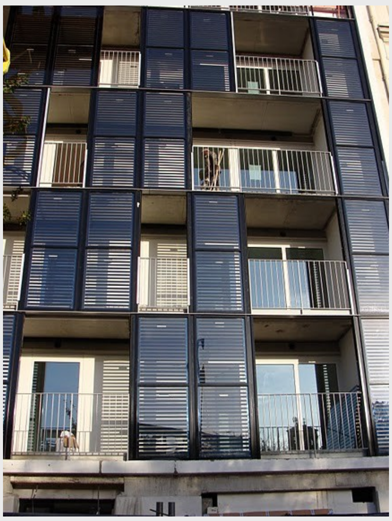
The RobinSun Solar Thermal Glass is a double-glazed insulating glass unit for fixed façade window frames (wood, aluminium, pvc) that integrates a semi-transparent solar thermal collector. It is a multi-function glazing system, since it contributes to insulation, natural lighting, production of domestic hot water as well as heating and/or air conditioning.
It is manufactured in 4 standard dimensions but other sizes and glasses are possible on the basis of custom request. The energy intercepted by the collector integrated into the glass is transferred by water circulation into storage and the hydraulic connections are fitted into the frames.
This product enables a very good integration for façades.
Constraints of this product are in the no possibility in choosing the absorber colour and the lack of dummies.

ST "Integrability" characteristics

Shape & size flexibility	+
Glazing: surface texture	+
Absorber: surface texture	+/−
Absorber colour	+/−
Jointing	+
Collector conceived as multifunctional construction element	+
Availability of dummies	−
Collector as par of a complete construction system	+/−







Credit: www.robinsun.com

Unglazed solar thermal collector

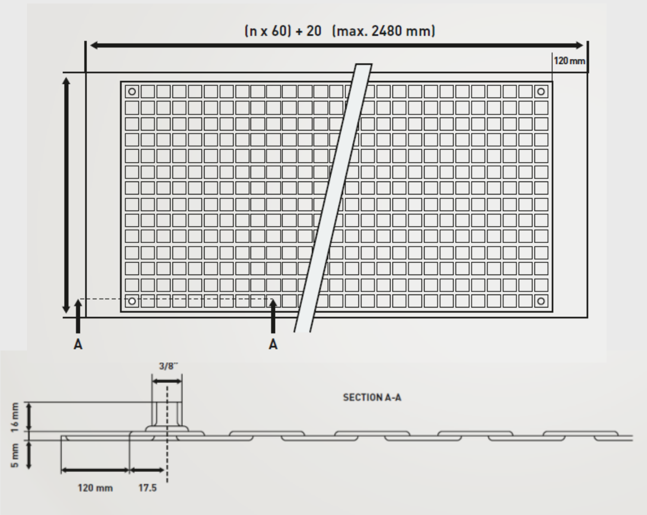
Solar roof - Energie Solaire SA

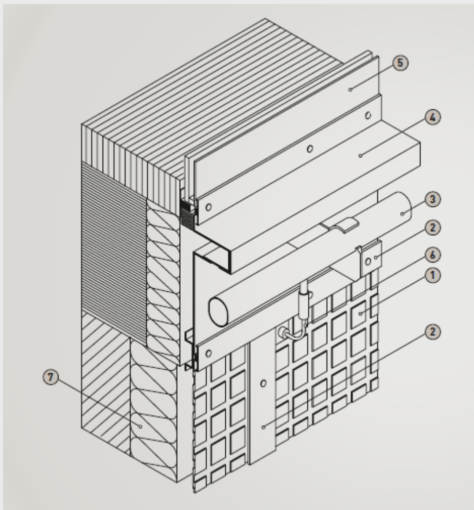
Z.I. Lle Falcon, – 3960 Sierre, Switzerland
info@energie-solaire.com
http://www.energie-solaire.com

The Energie-Solaire unglazed solar thermal collector is a plane heat exchanger, with a cushion geometry and a black chromium selective coating.
The absorber is a made out of two 0.6 mm thick stainless steel sheets, stamped and welded together. There is neither glazing cover nor peripheral insulation (α = 0.96 (solar absorbance); ε = 0.05 (thermal emittance)).
The absorber is conceived as a multifunctional element, for roof covering and facades cladding. The collector can be curved to be adapted to all typologies of roof, but there is no flexibility in surface geometry, colour and module sizes.
The collector is guaranteed for low temperature applications such as low temperature space heating, heating swimming pool and pre-heating of DHW. It is adapted for mild climate (South Europe).

ST "Integrability" characteristics

Shape & size flexibility	+/−
Absorber: surface texture	−
Absorber colour	−
Jointing	+/−
Collector conceived as multifunctional construction element	+
Availability of dummies	+
Collector as part of a complete construction system	+





Pictures from left to right: 1) Integrated solar roof , Swimming pool in Brebbia (IT); 2) Plurifamiliar building in Vilanova (E); 3) CeRN in Bursins (Switzerland). Source: EnergieSolaire.

Unglazed roof tile collectors

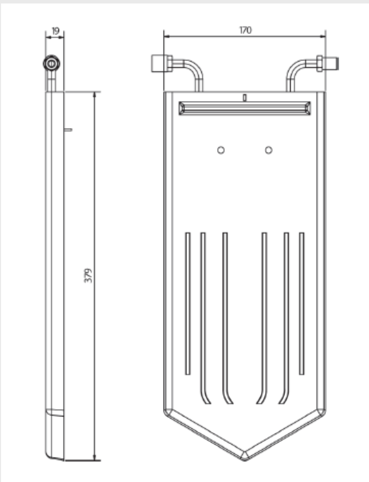
Atmova – Casta, Atmova

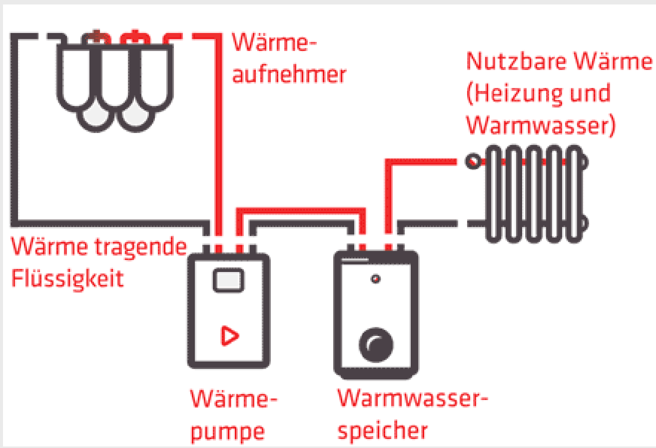
Weidenstrasse, 50 - 4143 Dornach, Switzerland
info@atmova.ch
http://www.atmova.ch

The Atmova covering is an unglazed solar thermal system with invisible heat recovery conceived to be integrated into the roof.
The copper tile integrates a hydraulic circuit in which an antifreeze glycol liquid flows.
There is some flexibility for the shape of the collector, since 3 different kinds of tiles are proposed according to integration needs. This kind of "solar tile" can be easily disguised among traditional tiles and so is easy to integrate as roof covering especially for historical buildings. It is also possible to cover just part of the roof according to the building energy demand and use dummies to complete the roof covering.
The constraint of this product is in the lower energy production compared to a classic unglazed flat plate collector, since a selective paint is not used on the surface. It is so necessary to connect the solar thermal system to the heat pump in order to have higher temperatures.
Module size: 170 mm x 379 mm. Weight: 1.9 kg.

ST "Integrability" characteristics

Shape & size flexibility	+
Absorber: surface texture	+
Absorber colour	+
Jointing	+
Collector conceived as multifunctional construction element	+
Availability of dummies	+
Collector as part of a complete construction system	+





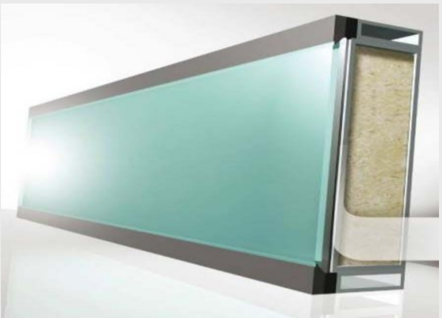
Credit: www.atmova.ch

Glazed solar thermal collector

Heliopan© BIST collectors

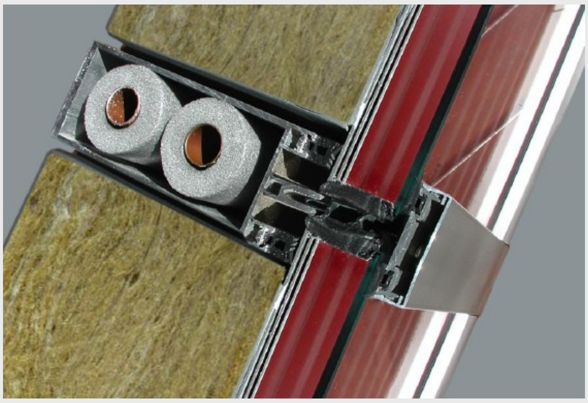
Kreuzroither Metallbau GmbH
Gahberggasse 9 - 4861 Schörfling am Attersee, Austria
http://www.heliopan.info

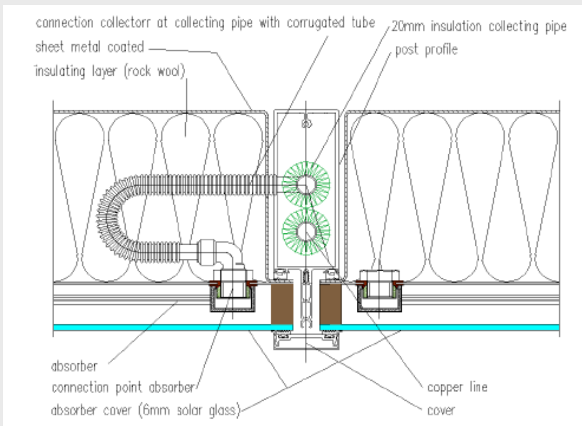
The Heliopan© BIST collector is a glazed solar thermal collector conceived to be integrated in a curtain wall of the building and in an aluminium glass facade.
The collector can be manufactured in any colour and can fit any size required in any façade system. The dimensioning can range up 2 x 4 m.
The collector is proposed for applications such as heating and cooling, eventually coupled with a HELIOPAN© BIPV to produce electrical energy as well.



ST "Integrability" characteristics

Shape & size flexibility	+
Glazing: surface texture	+/−
Absorber: surface texture	+
Absorber colour	+
Jointing	+/−
Collector conceived as multifunctional construction element	+
Availability of dummies	+
Collector as part of a complete construction system	+







Example of applications of the Heliopan© BIST collector . Credit: www.heliopan.info

Unglazed ST collector

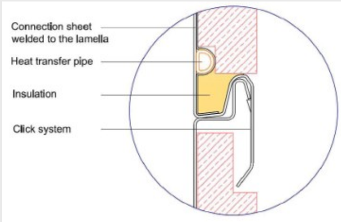
Solarfassade, WAF Fassadenelemente

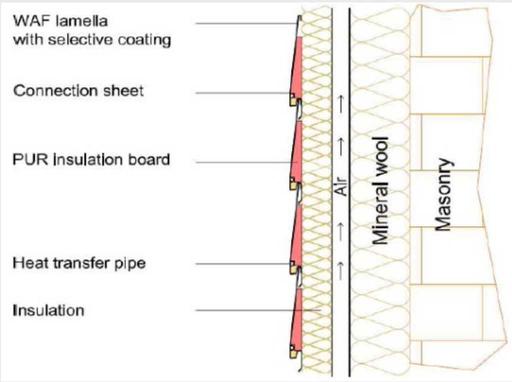
Gewerbezone, 3 - A - 6404 Polling in Tirol (A)
info@waf.at
http://www.waf.at

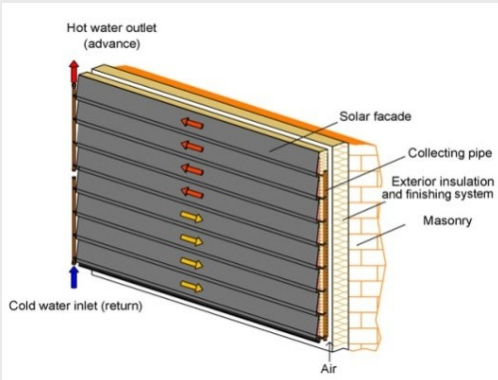
The WAF Solarfassade is a solar facade of WAF company, specialized in metal and glass facades.
The heating coil is hidden behind the metal cladding system and it is inserted into the layer of insulation made of PUR. A PU foam is used for filling possible cavities between pipe and insulation. Moreover, 50 mm of mineral wool are used to minimize the collecting pipes.
The surface of the metal panels is treated with a solar varnish, weather resistance (α_{black}=86%; ε_{black}=36%).
Dimensions and colours are customizable. Few typologies of panels are proposed such as shiplap panel and flat panel with or without shadow gap.
It is easy to assembly and architecturally attractive due to the easy integration in the envelope as cladding facade. The collector can be used for swimming pool heating and to provide hot water for domestic use and for a low-temperature heating system. In addition, it can be combined with a geothermal low-temperature system.
Module basic size: 2000mm x 1200mm x 50mm. Weight: 10kg/m².

ST "Integrability" characteristics

Shape & size flexibility	+
Absorber: surface texture	+
Absorber colour	+
Jointing	+
Collector conceived as multifunctional construction element	+
Availability of dummies	+
Collector as part of a complete construction system	+







Credit: www.waf.at

These products are quite promising, especially for the building renovation field but there is still the need to develop new products, since the offers on the market are just a few.

Regarding technical data of the two unglazed ST collector, proposed by EnergieSolaire and WAF respectively, the operating pressure ranges between $3 - 6$ bar to a maximum of 10 bar and a flow rate between 40 and 180 l/h.m^2. These data depends mainly on how the absorber is built, if as plane heat exchanger or as .

3.2.2 ST prototypes

In the research field, some prototypes of innovative solar thermal collectors have been developed inside European research projects. The three following prototypes show how synergic a collaboration between manufacturers and research centers can be. These challenges have had the aim to go over some limits of ST products and to propose new ones conceived as elements having a double or more functions in the envelope [3, 1].

Evacuated tubes collector s

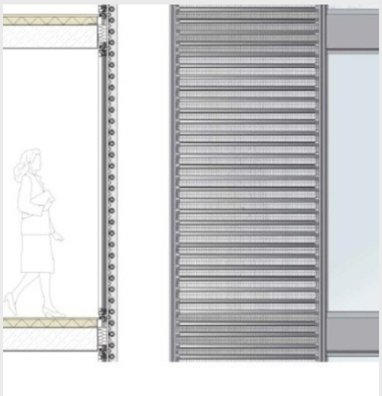
CPC Office/System WICONA, Facade collector

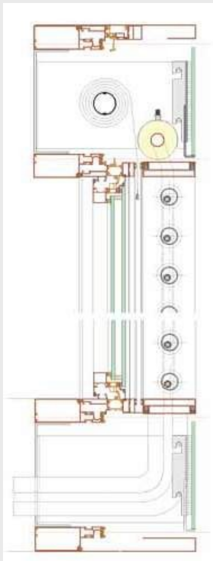
Project coordinator: Institute for Building construction and Design L 2 at the University of Stuttgart
info@ibk2.uni-stuttgart.de
http://www.uni-stuttgart.de/ibk2

This facade collector consists in vacuum tubes fitted with CPC mirrors to be integrated into modern building facades, e.g. offices as well as residential buildings, equipped with glass facades.
This product has been developed in close co-operation with some industry partners (Hydro Building Systems WICONA, Frener & Reifer Metallbau, Ritter Energie- und Umwelttechmik, Metallbau Frueh) and research partners (Technical University of Munich).
The product collects the sunlight and protect the rooms from direct solar radiation. High temperatures can be reached (60-90°C) and then is supplied to the building through a pipe system integrated into the facade profiles, making easier the maintenance. Part of the sun can penetrate the perforation of the CPC reflector into the building, providing a low-glare lighting in the room and visual transparency for the office users.
It has been conceived as multifunctional as well as modular product, virtually available in any size and with a high degree of architectural quality.
The product will be soon available on the market.

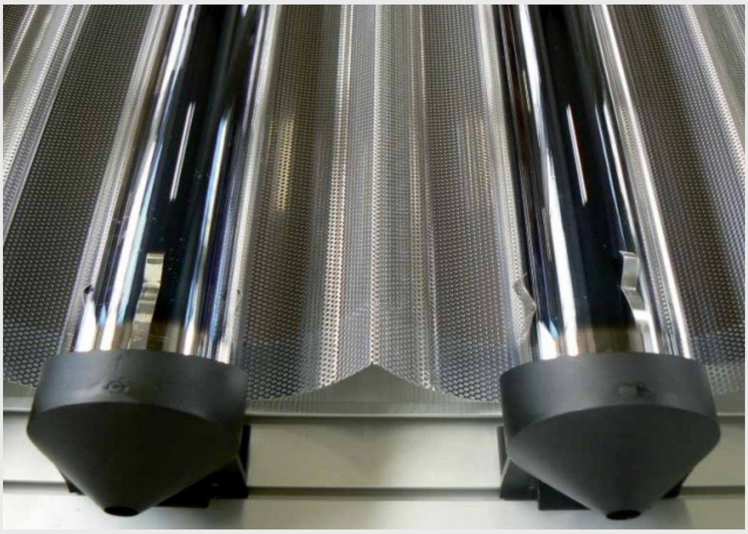
ST "Integrability" characteristics

Shape & size flexibility	+
Glazing: surface texture	+
Absorber: surface texture	+/−
Absorber colour	+/−
Jointing	+
Collector conceived as multifunctional construction element	+
Availability of dummies	+/−
Collector as part of a complete construction system	+





Orrizontal profile of a transparent prototype



Credit: www. paradigma-iberica.es and SHS IEA Task41

Glazed solar thermal collector

Fraunhofer ISE

Bionic Fracterm© absorber, Bionicol facade collector

Project coordinator: Fraunhofer Institute for Solar Energy Systems, Heidenhofstr. 2, Freiburg, 79110 (D)
http://www.bionicol.eu

This product was developed inside the Bionicol project (EU project – FP7: 2008-2011) by Fraunhofer Institute in close co-operation with some industry partners (TiSUN, CGA Technologies, INTERPANE, Tyforop Chemie).

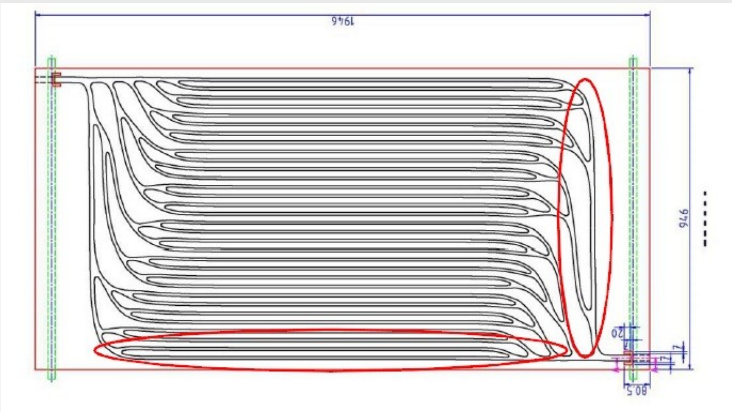
The developed solar thermal collector consists in an aluminium roll-bonded absorber with a Bionic Fracterm© channel. The channels are multiply branched in a fractal way in order to obtain a uniform flow distribution, a low pressure drop as well as a high thermal efficiency. The absorber is cover with a special coating and then mounted into a collector casing. One of the aims of this project was to produce an absorber with maximum efficiency and minimum costs. The product will be soon available on the market.

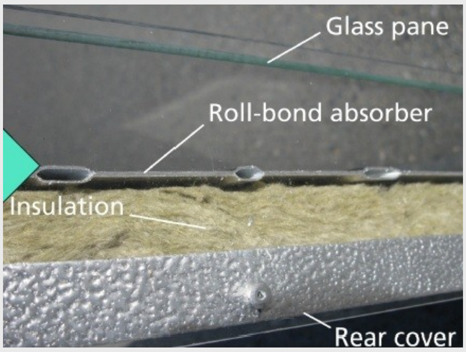
This collector is flexible in size, since it can be designed as parallelogram, triangle or arcs.

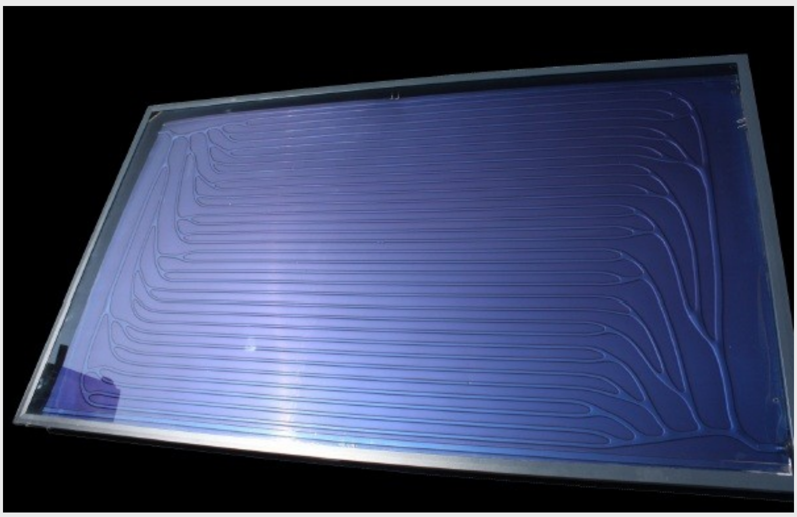
It is proposed to be integrated on roofs and in facades but it was not though to be as a integrated element of the envelope.

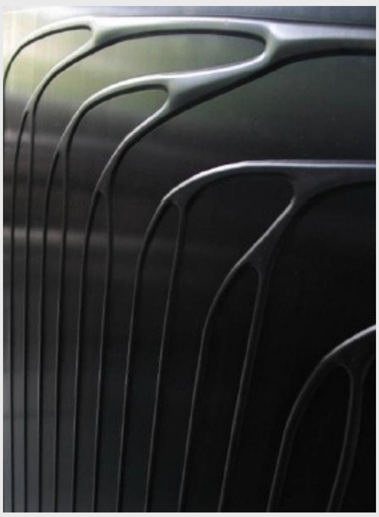
ST "Integrability" characteristics

Shape & size flexibility	+
Glazing: surface texture	+
Absorber: surface texture	+
Absorber colour	+/−
Jointing	+/−
Collector conceived as multifunctional construction element	+/−
Availability of dummies	−
Collector as part of a complete construction system	−









Credit: www. Bionicol.eu.

Unglazed solar thermal collector

Solabs®, facade collector

Project coordinator: Fraunhofer Institute for Solar Energy Systems, Heidenhofstr. 2, Freiburg, 79110 (D)
http://www.solabs.net

This product was developed inside the Solabs project (EU project FP5, 2003-2006) by Fraunhofer Institute in close co-operation with other research partners (LESO-EPFL - Switzerland, National Institute of Chemistry –Slovenia, Universidad de Malag - Spain) and industry partners (CLIPSOL, INTERPANE, Thyssen Group, Planair SA).

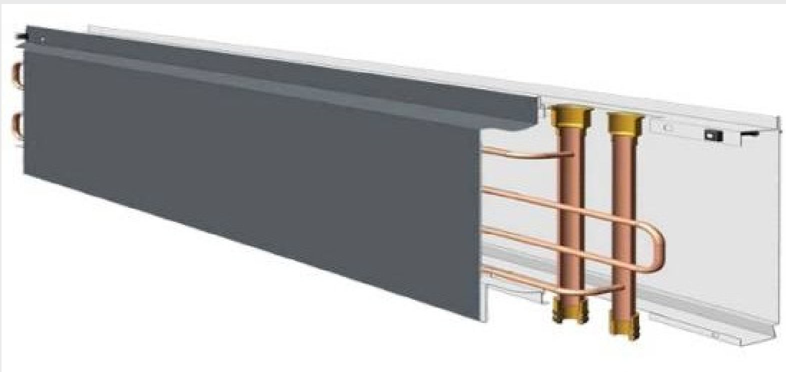
The task was to develop an unglazed, colored facade collector based on coated steel sheet. Steel-based solar collectors have been developed for application as facade elements in steel construction. The design of the collectors has been an important element of this development, allowing them to be integrated into the architecture of buildings and gain greater acceptance for solar heating.

The basic idea was to develop a façade metal cladding with the double function to cover the façade and produce hot water.

The prototype is not available on the market.

ST "Integrability" characteristics

Shape & size flexibility	+
Absorber: surface texture	+
Absorber colour	+
Jointing	+
Collector conceived as multifunctional construction element	+
Availability of dummies	+
Collector as part of a complete construction system	+



Credit: http://leso.epfl.ch/page-37325-fr.html and http://www.aee-intec.at/0uploads/dateien638.pdf

3.3 Solar thermal facade application in building renovations

The present section is dedicated to some examples of building renovation in Europe with integration of solar thermal collectors in facade.

3.3.1 Example of an office building renovation

A good example of energy retrofit action of a non residential building is the renovation of Stahlbau Lamparter's office building in Germany [4]. The facades of the building, constructed in the 1960's, have been renovated with a steel and glass curtain wall, with integration of solar thermal collectors.

(a) South facade of the head quarter of Lamparter Stahlbau GmbH & Co. KG before the renovation in 2008.

(b) The building after the renovation.

Figure 3.1: Heinrich Lamparter Stahlbau GmbH & Co. KG office building. Energy retrofit action with integration of solar thermal collector in facade. Kassel (D). [4]

The integrated full-glass collector has been developed to combine some functions such as heat protection, insulation and heat production. The collector is based on a triple glazed windows and the absorber consists in an aluminum roll-bond plate integrated in the triple glazing. The space is filled with Argon to reduce heat losses. The full-glass collector is characterized as well by a low thickness and this makes this product suitable for building renovation. The collector piping is contained in a hydraulic case in the space above the collector.

The solar energy system coupled with the facade collector is a pilot plant as well. Indeed, no standard components for energy system like this one are available for commercial or industrial buildings. The system is equipped with a storage tank of 5000 liters with an internal heat exchanger being able to reach a power of 210 kW at 45°C for supplying of DHW. An auxiliary heater of 50 kW is as well integrated. The solar loop is connected to the storage via an external heat exchanger and an integrated stratification pipe.

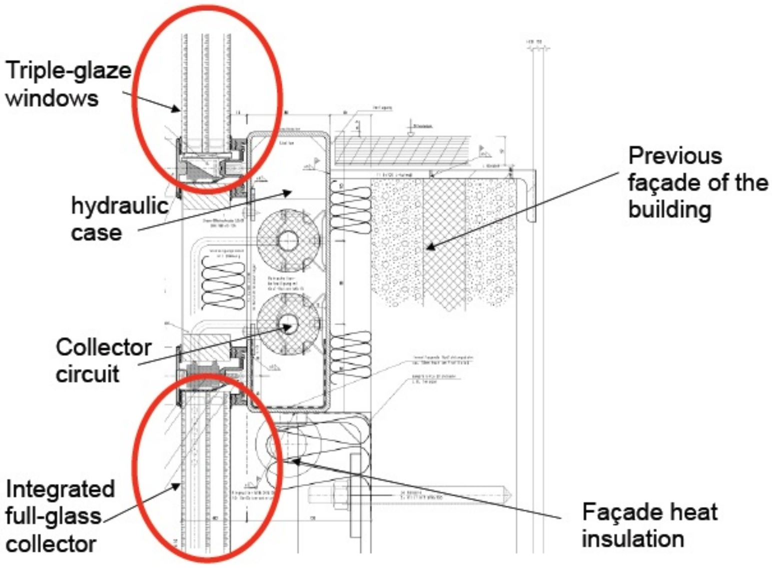


Figure 3.2: Vertical configuration of the integrated full-glass facade collector developed by the Energy Glass GmbH.

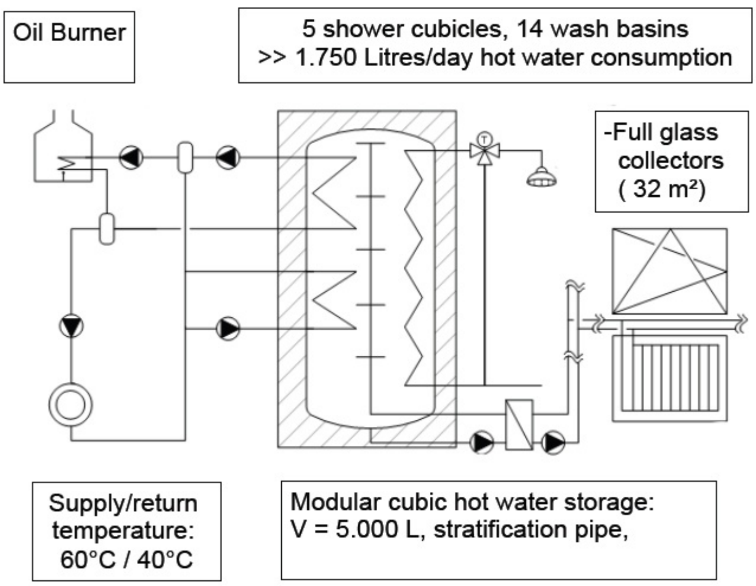


Figure 3.3: Energy system of Lamparter's office building.

3.3.2 Example of a residential building renovation

The residential building stock of Dieselweg in Graz (AT) represents another good example of energy retrofitting. It consists in a large scale action on very poor and energy inefficient buildings, constructed between 1945 and 1980 [5]. As already described in section 2.2, the Dieselweg block is characterized by the application of prefabricated module on the existing facades. In the south facade of the block, modules integrating solar thermal collectors have been implemented. The substructure on the existing facade have been filled with mineral wool and the pipe connection have been completed after the assembly.

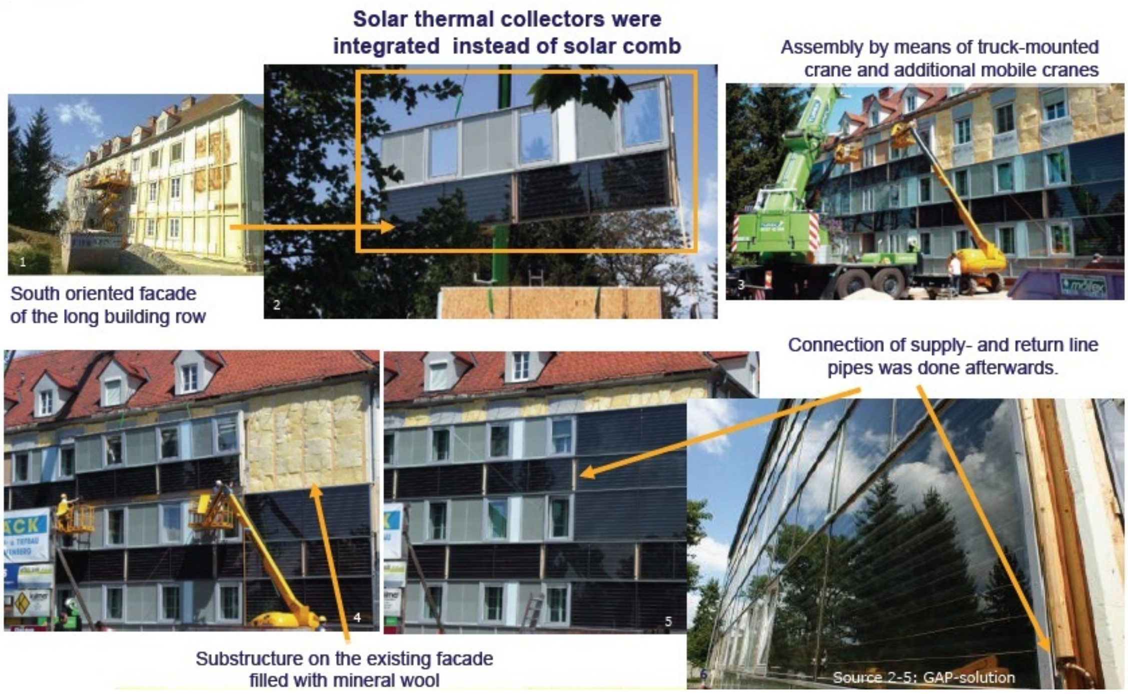


Figure 3.4: Solar facade modules application in the south side of the building block in Dieselweg in Graz (AT).

3.4 Solar roll-bond absorber

3.4.1 The solar thermal collector absorber

The heart of a solar collector is the absorber, which has the function to collect the solar energy and transfer the heat to the fluid flowing in the pipes connected to the absorber. Absorbers are made of copper or aluminum and are characterized by a dark surface in order to reach a high degree of light absorption, that is the amount of short-wave solar radiation absorbed and not reflected.
The absorber warms up to a temperature higher than the environment temperature and gives off the accumulated energy in form of long-wave rays. The degree of emission indicates the ratio of absorbed energy to emitted heat.
To reduce the heat losses, the most efficient absorber has a selective surface coating enables the conversion of a high part of solar radiation into heat.

3.4.2 The roll-bond absorber

The absorber of the solar thermal collector can also be built with the roll-bond technique, usually used to realize evaporators for refrigerator systems.

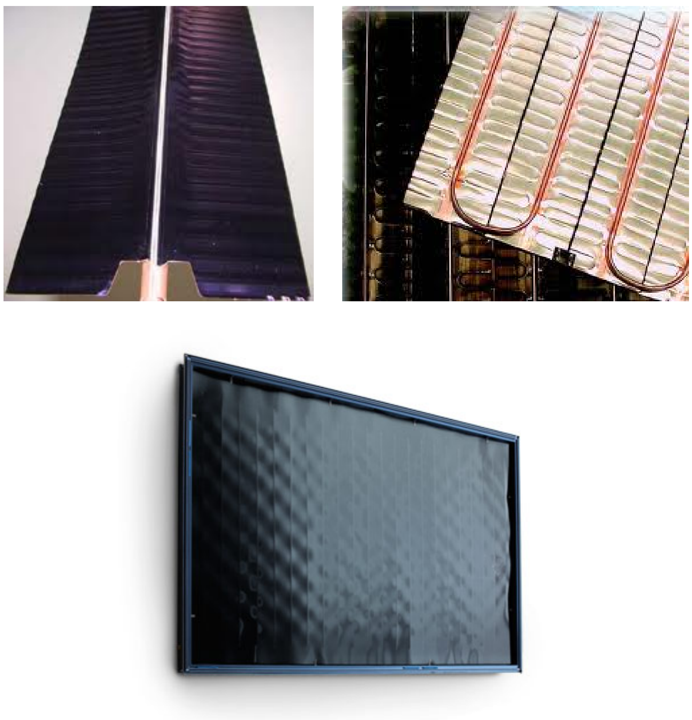


Figure 3.5: Different typologies of metal absorber proposed by different manufactures.

A roll-bond absorber is made with a sandwich of two aluminum sheets, using the technology of printing refrigerating fluid route, then heat it and roll welding by pressing air to make out a canalization, allowing the flow to have a very good heat exchange due to the high thermal conductivity.

The absorber presents a piping coming in and one coming out with corresponding openings for each.
The channels can have two main configurations: A) harp shaped parallel pipes, connected to inlet and outlet manifolds; B) serpentine shaped single pipe. Taking in consideration the first shape type, the fluid enters the roll-bond absorber homogeneously and it is guided by and distributed via the welding points inside the harp parallel shape, getting warmed up with the effect of solar radiation. The well distribution of the fluid inside the absorber should guarantee a good exchange and a higher efficiency.

One of the main issues of a roll-bond absorber is the typology of connections between two absorbers. Usually the connections are in copper aluminum and they can be blended but, in correspondence of the inlet pipe and the outlet one, they presents a weak point. In the case a faster connection is requested, it is necessary to individuate a suitable solution, since the pipe coming out from or entering in the absorber must to be connected to the next one in a such a way to avoid breaks and cracks and in general a weakness of the material.
An other important thing to consider is that the inlet and outlet pipes of the absorber are always on the shorter side of this one. In this way, if the longer side of the absorber is vertical, that means to have a vertical absorber, the pipes are at the bottom and at the top. If the absorber is in horizontal position, the pipes are on the left and on the right. This aspect is important in that moment we must choose to have absorbers connected in parallel or in series.

This technology presents a very good flexibility, since it allows creating a large number of different paths for the channels. In this way, the absorber can be adapted to any possible custom request. The aluminum sheets are very easy to be machined, bent, cut and painted and they can have a double canalization (on both sides) or a single one (just on one side).
The panel is usually realized in pure aluminum at 99.5%. Regarding the dimensions, the width ranges between 500 and 800 mm and the the maximum length between 4000 and 5000 mm. The thickness of the absorber depends on the rolling process, since a $4-5$ mm thick aluminium plate can be squeezed and brought to a thickness in the range $1.2-1.6$ mm with a double layer of aluminium sheet.

Moreover, the canalization could be:

- *double* (on both sides): usually in pure aluminum at 99.5%. The plate is built with two aluminium sheets with a total thickness between 0.6 and 0.75 mm;

- *one side flat/one side canalized*: an aluminum alloy is usually used on the flat side to have more mechanical resistance and maximum deformation

(a) Example of roll-bond plate evaporator. (b) Fractherm absorber developed within the European project Bionicol by Fraunhofer.

Figure 3.6: Different typologies of metal absorber proposed by different manufactures.

on the canalized side. The thickness ranges from 1.2 mm to 1.5 mm. In this case, the weight of the panel is higher.

One more roll-bond exchanger feature is the low unit cost.

This technology can be applied in several fields as solar panels, radiant panels for the conditioning systems, cooling circuits of engines/transformers as well as evaporators fro refrigerators.

3.4.3 Applications of roll-bond absorber in the solar field

In Europe, there are some companies proposing a roll-bond plate as absorber for a solar thermal collector or as absorber for a photovoltaic-thermal (PVT) system.

In addition to the prototype Bionicol developed by Fraunhofer, in Europe there are a few products on the market of unglazed solar thermal collectors having as absorber a roll-bond plate. These products are proposed as element to add on the roof or in the facade, but they do not represent a good example of integration from the architectural point of view.

In the PVT systems, the roll-bond absorber is used to cool the PV system in order to improve the energy efficiency in summer-time. The collected heat from the water-glycol mixture can be sent to a water-air heat-exchanger or to a swimming pool, getting a double benefit.

Figure 3.7: Unglazed solar collector proposed by Energy.pt. Source: www.energie.pt

In conclusion, the roll-bond technology has a great potentiality if used as absorber of an unglazed solar thermal collector.
However, there are some engineering and architectural issues to analyse and to solve, in order to make attractive this product for the integration into facades. An important aspect to take into consideration in designing a well-conceived unglazed solar collector is that a metal unglazed collector is also a metal cladding.
In the next section, the metal cladding systems are described in order to individuate the best solution for the unglazed collector.

Figure 3.8: PVT system proposed by Beghelli. Source: www.beghelli.it

3.5 Metal cladding facade systems

The use of the metal for the "over skins" of buildings is ideal for conveying a "high-tech" aspect, especially to commercial and industrial buildings as well as to public buildings as hospitals, schools and sport facilities. The typology of building is important for the design of metal facades because it is often necessary to match the material and the cladding system with the other elements of the building as windows and exposed metal load-bearing sections.

3.5.1 Short history of the metal use into facades

The use of metals in the building facades coincided with the development of rails for the emerging railway industry (from 1830) and the introduction of steel (from 1855). The use of metal enables a high degree of prefabrication as well as great precision. Generally, the steel and iron elements on the facades were used as part of the load-bearing structure, often in combination with glass and clay bricks. Cast iron was typically applied in the 19th century in the prefabricated balustrades, panels and systems for balconies and arbours. One of the first examples of an opaque metal facade is the office building by Georges Chédanne in the Rue Réaumur in Paris (1905) (see 3.9)[6].

Figure 3.9: Metal facade in Rue Réaumur in Paris of Georges Chédanne, 1905, France.

At the start of the 20th century "standard steel sections", optimised for some loading cases, began to appear, together with the development of special facade sections and elements.

The Maison du Peuple, Clichy (1939) (see 3.10(a) and 3.10(b)) of the French engineer Jean Prouvé is a very good example of application of cladding to a multifunctional and flexible building: civic and cultural centre, market, auditorium for 2000 people and cinema for 500. The facade claddings are in glass and metal and the maximum metal sheet size is 1.2 by 4.0 m.

(a) Facade of the offices of the "Maison du peuple", Clichy (F), 1939, Jean Prouvé.

(b) Renovation of the Maison de Peuple, 1988.

Figure 3.10: Maison de Peuple of Eng. Jean Prouvé, 1939, France.

As a designer and manufacturer, Prouvé developed the concept of the curtain-wall, metal cladding systems and infill panels for walls. He wielded a considerable influence over later designers and architects who, from the 1960s onwards, promoted the use of metal for prefabricated panels and sandwich construction by improving the manufacturing and jointing techniques employed [6].

In Europe the first proper curtain wall facades started to appear after about the 1955.

3.5.2 Metal cladding systems for facades

The cladding is one of the most expressive and complex aspects of the building facade design. As external component of the envelope, cladding has to provide critical and complex functions in a series of varied relationships:

- protection from rain, wind, noise and security from intrusion;
- comfort - light, humidity, sound, ventilation;
- sustainability, maintenance and durability.

There are many forms of cladding system depending on types of material used - stone, concrete, ceramics, steel, aluminum and other metals - and means of installation.
Some important cladding terms which are often confused include:

- curtain wall: a non-load bearing external wall
- rainscreen: it comprises some layers each with a separate function

- overcladding: the addition of a new skin over the existing.

Curtain wall is a general term used to define a non load-bearing external wall (opaque or glazed), supported from a structural wall. The definition usually is not so precise. It is most often used in connection with factory produced repetitive elements of framing and panels of glass or opaque materials. In this context, the development of curtain wall is almost synonymous with the development of multi-storey framed buildings.
Rainscreen cladding defines a multi-layered system, each of the layers performs a separate function with regard to weather, insulation and ventilation.
Overcladding is the addition of a new skin of cladding applied on the existing cladding, often in order on one hand to improve the thermal insulation and the appearance, on the other hand to minimise or eliminate deterioration of the existing building [7].

3.5.3 Cladding system features

As component of the building envelope, a cladding system must provide some technical requirements: environmental, performance and structural requirements.

environmental requirements: a building should provide an acceptable level of *thermal comfort* with a minimum environmental impact. Current building regulations require minimum thermal standards for cladding. The type of cladding adopted is a primary factor in the method through which thermal comfort will be achieved. Furthermore, the *durability* of cladding is as well an important factor in relation to exposure, materials and finishes. The durability depends on many aspects including specification of materials, compatibility of different materials, climatic factors such as rainfall and exposure to solar radiation and detailing and workmanship. Compatibility of materials is important in order to avoid bi-metallic corrosion (it can take place when two different metals connected together get wet). In the case of aluminum, it is known aluminum rapidly forms a protective oxide layer for its corrosion resistance and under right conditions.
Performance requirements: the cladding systems must have an adequate *resistance* under static pressure and water flow and under dynamic conditions according to current standards.
Structural requirements: the cladding is usually subjected to *several loads*, due to the environment - e.g. wind - and occupancy, including self weight and impact loads. In the design phase it is considerable to avoid the collapse of the cladding system and excessive deformations that can compromise the structure static stability.
The structure and the cladding are the two principal components of the building facade and the connection between them is critical both in the installation phase and in the performance of the envelope. In the interaction between

structure and cladding, it must consider load transfer and relative movement. The structural connections of the cladding to the structure have the aim to transfer the different loads, e.g. self weight or wind loads, and adapt relative movement and construction tolerances. Generally, pre-fabricated elements are more accurately made than on site construction. In the end, good detailing of cladding is an essential point for a good performance.

3.5.4 Material properties

Most of the metals used in building facades - steel, aluminum, copper, titanium-zinc and bronze - are not employed in their pure form, but as alloys. Usually metals used in facade cladding systems content a primary metal $> 90\%$.
The most common and significant physical phenomena to take into consideration in the design phase because connected to the material/s used for cladding systems are mainly [6]:

- thermal dilation: it is responsible for movements which have to be accommodated by appropriate forms of jointing and assembly;
- corrosion: environment influences and alters the surface appearance of the most of these metals. The corrosive process is a great problem because need to be renewed frequently and this implies higher maintenance costs. Some metals do not corrode, others form a regenerative anti-corrosion layer which changes the appearance with the time, e.g. the copper. A third group - iron and steel - required special treatments in order to resist environmental influences.

Usually between the facade cladding and the insulation layer, it is foreseen at least 20 mm of a ventilation space according to the standard DIN 18516. Generally this typology of system present 40 mm of ventilation layer. Moreover, the open joints of ventilated/rainscreen facades allow air to flow freely into and out of this envelope area. The unrestricted air movement produces three very useful benefits:

- the flow eliminates pressure differences that would tend to blow water further in. This means little if any water makes it across the air gap to reach the inner shell;
- the air flow dries any moisture within the envelope area, such as rain that might be trickling down the back of the outer shield;
- the air envelope acts as an insulating barrier by minimizing thermal bridges and preventing heat buildup within the envelope.

3.6 Plank and cassette cladding systems on the market

The use of metal products represents a new way to plumb technology and facade construction for new buildings and for the refurbishment of old buildings. In Europe, there are manufacturers proposing metal products that can be used to realize various system elements such as system rhomboids, profiled sheets, profiled panels, cassettes and planks.
The metal profiles that can fitted also to be unglazed thermal collectors are mainly the plank and the cassette systems. Here following the state of the art of cassette and plank system and the comparison of the two cladding systems in order to individuate which of them gives the best answer to the technical and architectural requirements for an unglazed solar thermal collector made with the roll-bond technique.

3.6.1 Plank system

The **plank** profile is a facade cladding element which is bent on two sides. The planks can be produced according to design specifications and usually tailor-made. As cassettes, plank profiles are used in curtain walls as large components for easy, quick and cost-efficient installation. The plank, also called lamella or panel, cladding as well as the cassette cladding is usually constructed as a bracket-mounted ventilated facade. In Europe, there are some manufacturers of metal claddings offering both plank and cassette systems. A comparison between these two typologies of cladding system is given in order to individuate the most suitable system to be apply also as unglazed solar thermal collector, considering also the roll-bond technology.
Firstly, plank system products of three different companies are presented:

- KME-TECU
- Rheinzink
- RUUKKI

3.6.2 Cassette system

Cassettes are facade cladding elements which are folded on all four edges and can be produced according to planning specifications and usually custom-made. The cassette as well as the plank cladding is usually constructed as a bracket-mounted ventilated facade. Moreover, the bonded edges allow even sheet metal parts to lie flush with the cladding surface.

Cassette system products of three different companies are presented:

- KME-TECU
- Rheinzink
- RUUKKI

	KME-TECU Klosterstrasse 29 49074 Osnabrück (D) www.tecu.com	Rheinzink Via De Gasperi 9 37010 Costermano VR (IT) www.rheinzink.it	RUUKKI Rautaruukki Oyj PL 138 (Suolakivenkatu 1) 00811 Helsinki (Fi) www.ruukki.com
Product	TECU panel	Horizontal reveal panel	Lamella CL10/20/30
Material	Cooper/Copper alloy	Titanium/Zink	Stainless steel / Copper / Aluminum (zinc coating, organic coatings - PVDF)
Technique	• Tongue and groove • Overlapping	• Tongue and groove • Overlapping	• Tongue and groove
Assembly	• Horizontally • Vertically • Diagonally	• Horizontally	• Horizontally
Fixings	• Visible • Concealed	• Concealed	• Visible • Concealed
Dimensions	• width up to 400 mm • length up to 4000 mm (it depends on the chosen surface and profile)	• width 200 – 300 mm • length 3000 – 4000 mm with max 6000 mm	• width 150 – 600 mm • length 150 – 4000 mm
Thickness	Composite material (TECU (R) BOND) of 2 sheets of 0.3 mm thick each with an interposed sheet of PE Total thickness 4 mm	1 mm or 1.2 mm when width is greater than 250 mm	
Wall construction	1. supporting structure 2. one-part or multi-part substructure 3. thermal insulation 4. ventilation layer 5. panel as cladding	1. supporting structure 2. mineral fibre facade insulation plates according to DIN18165 3. thermal insulation 4. two-part or multi-part metal bracket system substructure 5. ventilation layer 6. panel as cladding	1. supporting structure 2. lamella cladding

Table 3.1: Plank cladding systems of three European companies.

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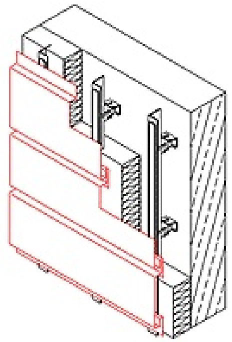
<td>

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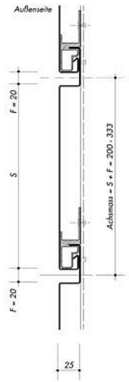
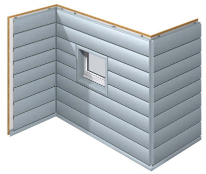
<td>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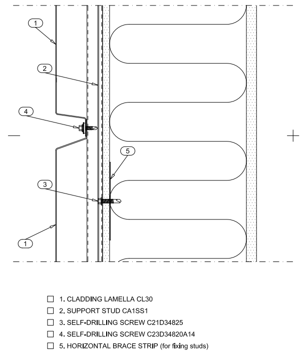
<td>

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</table>

Table 3.2: Plank cladding systems of three European companies (sources: KME-TECU, Rheinzink and RUUKKI) - pictures.

	KME-TECU	Rheinzink	RUUKKI
Product	TECU cassette	Rheinzink cassettes	RSP (Rainscreen panels)
Material	Cooper / Copper alloy	Titanium/Zink	Stainless steel/ Copper / Aluminum (zinc coating, organic coatings - PVDF)
Assembly	overlapping with folded edges on all sides	overlapping at all gaps, eventually vertically separeted	Horizontally or Vertically
Fixings	• visible • concealed	• visible • concealed	• Visible • Concealed
Dimensions	• Component proportions of 1:1 to 1:4 (ratio of length to width in visual range) cassettes are generally rectangular	• width > 333 mm to 890 mm • length 4000 mm with max 6000 mm	• width 500 – 2500 mm • length 500 – 25000 mm depending on the typology of RSP
Thickness	Composite material (TECU (R) BOND) of 2 sheets of 0.3 mm thick each with an interposed sheet of PE Total thickness 4 mm	1.2 mm and 1.5 mm	from 1.00 mm to 2.00 mm
Wall construction	1. supporting structure 2. substructure 3. thermal insulation 4. ventilation layer 5. cassette cladding	1. supporting structure 2. mineral fibre facade insulation plates according to DIN18165 3. thermal insulation 4. two-part or multi-part metal bracket system substructure 5. substructure 6. ventilation layer 7. panel as cladding	1. supporting structure 2. cassette cladding

Table 3.3: Cassette cladding systems of three European companies.

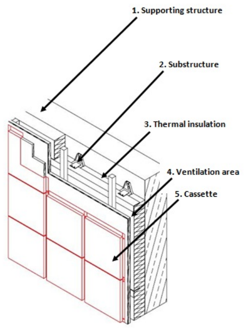
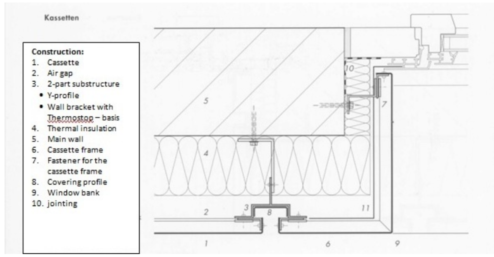
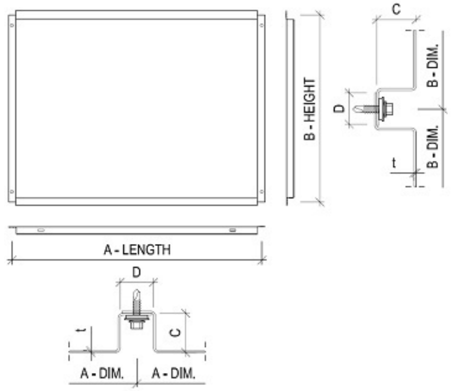
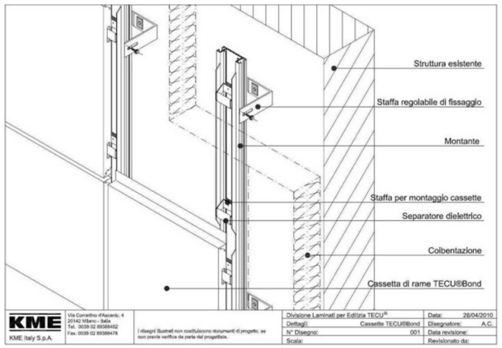
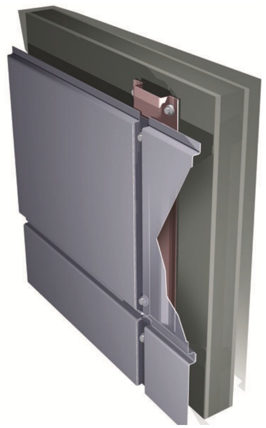
KME - TECU	Rheinzink	RUUKKI
		
		
		

Table 3.4: Cassette cladding systems of three European companies (sources: KME-TECU, Rheinzink and RUUKKI) - pictures.

3.7 Outlook

The state of the art shows, despite a few innovative products have been proposed on the market, there is still a lack of flexibility and a mismatch concerning the structural and architectural integration in the building envelope of some ST collector products and some prototypes developed inside European projects. There is still the need as well to develop new solutions for the building renovation market, with a higher degree of integration.

Moreover, there is a lack of experimental data about the energy and thermal performances of these products as well as lack of standards on solar thermal systems when integrated into facade.

Once the envelope typology and the building main characteristics such as materials, forms and colours are defined, the designer should have the freedom to choose among the ST collectors on the market the most compatible product, taking over the envelope functions and guaraanting continuity, equilibrium and coherence of the original design of the facade.

Thus, conceiving a ST collector as multifunctional envelope element means to design a product having as main function the collection of heat and at the same time being able to guarantee the standards structural and thermal envelope functions as well as to match the aesthetic characteristics of the building.

The next chapter 4 will detail the main contribution of this thesis which studies the possibility to merge the two technologies, roll-bond technology and metal cladding systems, into one product to answer both the engineering and architectural aspects.

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4

Integrating technologies: a novel aesthetic solar facade

4.1 Abstract

This chapter details the main contribution of this thesis. It presents the study on the possibility to merge the two technologies, roll-bond technology and metal cladding system, into one product to answer both the engineering and architectural aspects related to the integration of solar thermal in the building envelope.

The real core of the thesis is the methodological approach developed to address the design of the unglazed solar thermal/facade cladding system following different steps:

1. description of the technical and architectural integration problems to select the proper suitable cladding system between plank and cassette;
2. heat transfer and fluid dynamic assessment of the physical interaction of the new facade on the existing one through a finite element method tool in order to address the design;
3. modeling of the energy system of the Building Integrated Solar Thermal (BIST) through the TRNSYS dynamic simulation tool.

Chapter 5 will detail the analysis of loads for DHW and space heating of some residential and non-residential buildings. They have been carried out through EnergyPlus simulations considering the DOE's benchmark models with the aim to define the reference buildings for this application [5].

In chapter 6, the model of the BIST energy system is described in details.

4.2 Integrating technologies in the envelope: a novel aesthetic solar facade

As seen in the previous chapters, the European building stock is old and needs renovations, with the global objective of zero net (or nearly) energy balance of buildings. Building envelope elements have a high impact on energy performance and it represents a new challenge for engineers, manufactures and architects whose interest in Buildings Integrating Solar Thermal (BIST) has been increasing.

The context analysis provided first a breakdown of building stock, in particular in terms of energy consumptions. Afterwards, the state of the art provided an overview on the solar thermal technologies available on the market and cladding systems both for facade applications. These fundamentals stated, it is now possible to show what there is still to do in the building field to make the diffusion of ST technologies easier and to go deeply in detail about the design of a new solar technology integrated in the facade.

In the concept design and development phases of a new solar thermal technology for facade, there are complex structural and architectural issues to deal with. The guidelines developed in the SHC IEA Task 41 for architects and solar technology manufacturers [2] describe the steps to do for architectural integration of solar technologies in the envelope. These criteria are summarized in the next section.

4.2.1 Criteria for the integration in the building envelope

When a ST technology is integrated in the facade, it substitutes some envelope functions such as controls and protection, and the envelope acquires the function to collect heat as well. As a result, we have a new multifunctional envelope. The integration must be coherent and controlled from the functional, constructive and formal points of view as deeply described in [6].

The integration of a ST system in the envelope requires, the building design team, an effort to identify where, how and which typology of ST collector can be more coherent with the other elements, materials and functions of the envelope.

Structural/constructive integration

A solar thermal technology can be implemented in different parts of the envelope and adapted to replace some of them on the basis of type of technology, e.g. evacuated, glazed or unglazed collector: the evacuated flat plate can be integrated in the facade as balcony eaves or sun shading (see product swisspipe of Schweizer-Energie or prototype developed by Universitaet Stuttgart and Frener&Reifer), the glazed collector as facade cladding (see Aksdoma) and the unglazed collector as metal cladding (see EnergieSolaire).

It has to meet different requirements and to be compatible with the materials, shapes and structure of the envelope. The technical issues to deal with are about the thermal, static and hydraulic aspects. Firstly, as an envelope element, the collector must meet the standard building constructive constraints such as:

- wind and frost resistance and safety in case of damage;
- fire as well as weather wear and tear resistance;
- transfer of the collector load to the load-bearing structure through the fixing system;
- no thermal bridges in correspondence of fixing points;
- no negative effect on the global U-value of the wall, once the ST collector is implemented;
- no vapour transfer through the wall to avoid condensation among layers and allow the wall to dry properly.

In addition, the integration of a solar thermal system in the envelope implies some problematics due to the hydraulic system.

The differences of water pressure at different heights of the facade must be evaluated carefully by the designer, who must foresee a safe position for the hydraulic system within the structure of the envelope as well. In case of damage due to water leakages, the pipes must be easily accessible. These last must not damage the insulation layer behind the collector absorber and possibly not interfere with the fixing structural system to the wall.

Beside water safety issues, it is as well important to evaluate the envelope materials expansion with the high working temperatures. Fixings details and jointing must be designed carefully to be compatible with the materials and to ensure the durability of the envelope. At the same time, safety measures must be taken in order to avoid the user's contact with the exposed surface of the absorber, in particular with metal unglazed ST collectors. It is strongly recommended to locate the collectors considering safety regulations.

The solar facade system must be as simple as possible and be easily accessible for maintenance.

Architectural/aesthetic integration

In the path of developing a novel solar facade, it is also important to cope with the architectural/aesthetic issues, since a building captures our attention firstly because of the visual aspect of the facade. Usually a building looks innovative because the facade is innovative.

The flexibility offered by some collector characteristics, listed below, has a great clout on the appearance of the facade and defines the level of integrability of a ST collector:

- position and dimension of the ST collector system;
- module shape and size;
- collector colour/s and visible surface texture/s;
- jointing typology.

Clearly, the more the product offers a high flexibility, the higher is the integration potential. In this way, it is not the product that defines form, material and colour to designers and users, but it becomes possible to match the aesthetic/formal features of the solar technology with the facade design and therefore with the energy need.

4.2.2 An innovative concept of solar facade

Looking at the unglazed ST collector market (see section 3.2), a few products built to be implemented in facades recently came out. However, constraints and flexibility limit the selection of dimension and colour of the absorber and their variety of applications.

Since a metal unglazed solar thermal collector conceived for facade is nothing but a facade metal cladding, the current project means to explore the possibility to merge two technologies into one product to answer engineering and architectural aspects/problems:

1. Roll-Bond technology used as absorber of an unglazed ST collector (UST), to answer the energy aspect;
2. Metal cladding system (cassette or plank) for the facade application, to answer the architectural/aesthetic aspect as well as the plug & play functionality of the product.

The obtained product is an active facade with the double function of producing energy and covering the facade in an automated easy to deploy manner.

4.2.3 Methodological approach

The adopted design method has for purpose to propose one hypothesis of configuration for the unglazed solar thermal/facade cladding system (see the structure in Figure 4.1).

Starting from the state of the art of roll-bond technology (see section 3.4) and metal cladding systems for facade (see section 3.5), the first step is the description of the existing technical and architectural integration problems and constraints by merging the two technologies. The objective is to select the proper cladding system between plank and cassette options, and propose a first configuration of the facade system.

Once the facade configuration is selected, it is important to understand how the new added facade and the existing one interact together from the physical point of view. A heat transfer and fluid dynamic assessment of the facade configuration is done through a finite element method tool to define the final hypothesis of configuration as well as to propose a valuable solution for the physical integration of hydraulic connections, support structure and cladding on the existing facade.

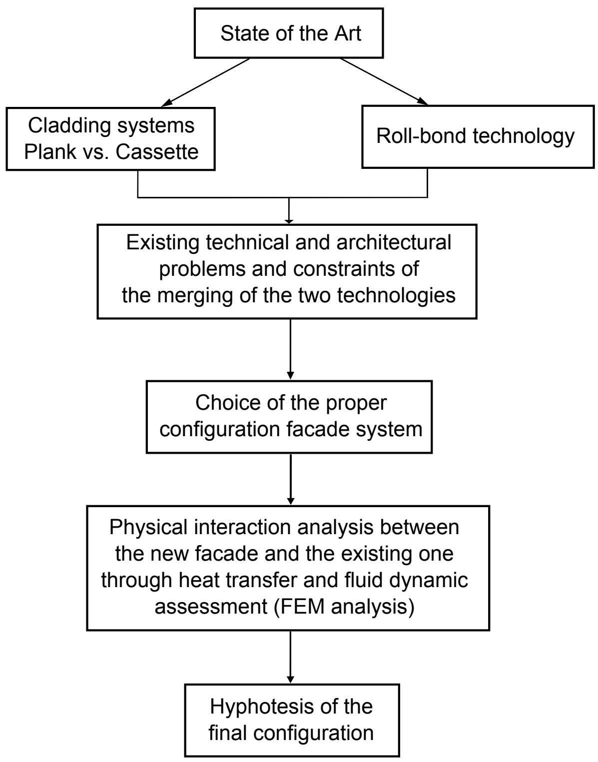


Figure 4.1: Structure of the methodology aiming to address the design of the facade solar component.

Once defined the technical and geometrical characteristics of the unglazed solar thermal element, the methodological path is afterwards addressed to define a model of the BIST energy system through the TRNSYS dynamic simulation tool. This part of the work aims to investigate the potentiality of the BIST to cover the heat demand for a combisystem for combined domestic hot water and space heating of some typologies of building, taken as reference buildings, in three different climate locations. In particular, the objective is to evaluate the energy performance and to define sizing procedures for the combisystem, in order to decrease the use of the back-up by means of an optimal solar source's utilization.

4.2.4 Configuration of the solar facade system

The first step of the approach is to select the proper suitable facade metal cladding for the development of the solar element. Both the cladding systems, described in the section 3.5, are valid options to be coupled with the roll-bond technology.

The potentiality of both the cassette and the plank is equivalent. The **cassettes** are modular elements with geometrical proportions from 1:1 to 1:4 and they can be assembled in two ways, with overlapping of folded edges on all sides or just on two of them or hanging by the support substructure. Otherwise the **planks** need to be cut-to-length modules with a width from 200 up to 600 mm and a max length up to 4000 mm. They are usually assembled with overlapping or tongue and groove technique.

Some technical and aesthetic requirements and constraints imposed by the roll-bond technology must be taken into consideration in the selection of the cladding:

- limits in size, thickness and material, since they have a strong effect on the mechanical resistance of the absorber panel;
- presence of two openings or windows in the absorber panel in correspondence of the two inlet/outlet pipes. The position and size of the windows can be changed, according to hydraulic connection modalities among collectors;
- presence of a “non active” space around the “active” part of the absorber, where the canalization is placed;
- application of an insulation layer behind the absorber in order to decrease heat losses.

Moreover, there is a wide range of configuration options which the designer and user can choose:

- canalization of the absorber on one side or on both sides, to hide the new cladding function of collecting heat rather than to emphasize this function and show the benefit from the absorber, giving thus an additional value to the cladding system;
- jointing between cladding can be visible or concealed (negative jointing);
- windows in the absorber panel can be emphasized as distinguishing elements or hidden according to the aesthetic requirements of the facade;
- colour of the selective paint coating for the unglazed STC on the sight side of the cladding system.

Balancing roll-bond constraints, geometrical specifities, assembly and maintenance eases of the claddings and the variable aesthetic preferences of the designers and users, the cassette option has been selected.

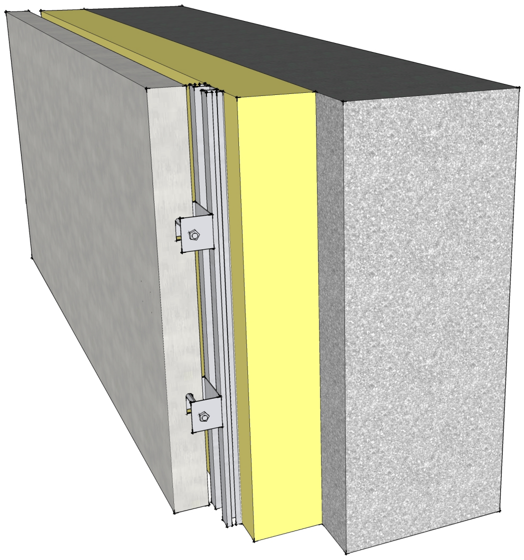
The cassette technology shows more freedom in case of maintenance and dismantling and moreover it has not been developed yet as solar element for the market and in the research field, while examples of solar plank applications have been developed by WAF and inside the European project SOLABS (see sheets in the section 3.2).

A first configuration of solar cassette is so proposed. It is a module element folded on the four edges with a surface of less than 1 m^2, considering the mechanical/static resistance of an aluminum panel. The panel has a geometrical proportion of 1:2 width/length and with negative jointings variable in width on the basis of the support structure. It is hanging to the substructure through anchor brackets and bolts.

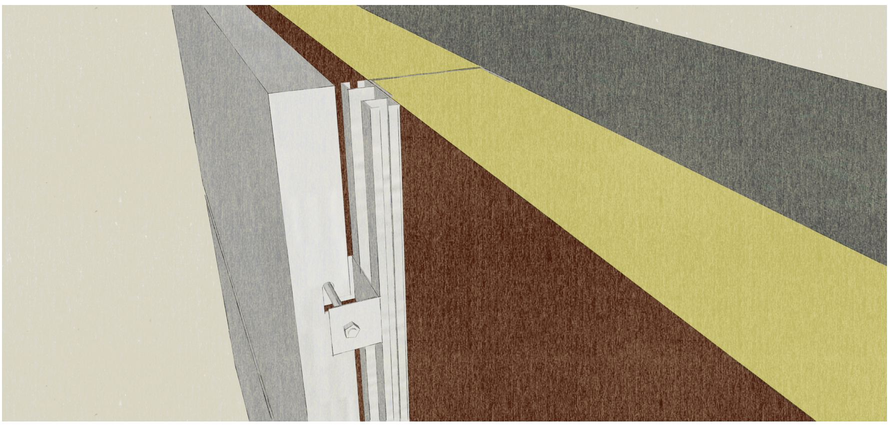
The roll-bond canalization is present just on one side of the absorber, while the other side is flat. Behind the absorber, an insulation layer made of expanded polyurethane is applied to decrease the heat losses of the fluid running in the absorber canalization. The insulation should not interfere with the pipes coming in and out from the absorber, since they must be easily accessible for maintenance actions.

A first sketch of the solar facade is showed in the Figures 4.2(a) and 4.2(b). The existing facade could be a generic wall structure with a thermal mass layer made of bricks or wood or cement and with an insulation layer. The sub-structure for anchoring the cassettes consists of vertical uprights, fixed to the wall through metal brackets. The connection between the cassette and the uprights of the facade is achieved by means of adjustable anchor bolts. The cassettes are provided with two snap hooks on both of the two vertical sides, in order to facilitate the assembly and the dismantling of every single element without compromising the others.

Basically several aesthetic solutions can be proposed for the solar cassette element depending on the facade designer's needs. It is possible either to hide the added function of the cassette to produce hot water or to increase the value of such a new function by emphasizing all those elements (windows, pipes and connections among pipes) or specifities which give the facade a different and pretty innovative aspect.
It is possible to play with alternation of elements to create rhythm and equilibrium in the facade. Several design possibilities could be developed considering the canalizations, presents on both sides and with different canalization geometries, the visibility or not of the windows and thereby their position in the absorber, as showed in Figure 4.3. The windows can be hidden using a metal patch or pointed out using a coloured frame around them or a coloured patch. In this way, it can play with alternation of elements to create rhythm and equilibrium in the facade.



(a) View on the solar cassette, the substructure, and the existing envelope – insulation and thermal mass.



(b) View on the substructure: the solar element is hanged to the substructure by means of bolts and anchor brackets, supporting the vertical uprights.

Figure 4.2: Solar facade sketches [Source: Arch. G. Paoletti]

Clearly for each aesthetic option, it is necessary to develop, as well, technical solutions regarding the hydraulic circuit, e.g. the delivery or distribution pipes of cold water and the collecting pipes of hot water, and the substructure, considering the advantages to dispose also of non active elements known as dummies.

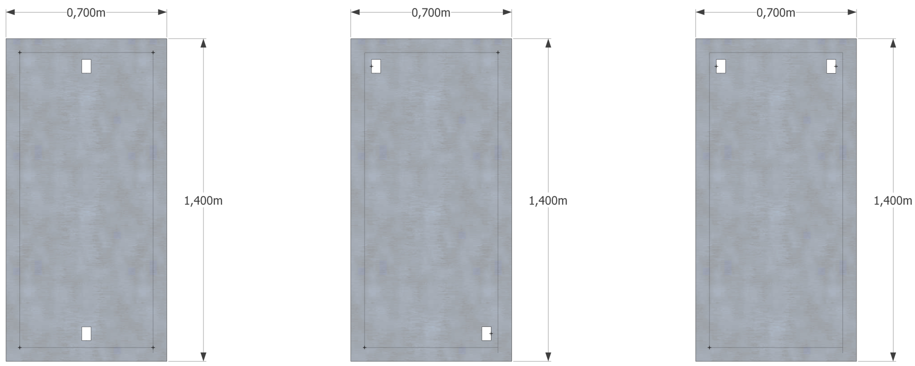


Figure 4.3: Design possibilities for windows' positions, for the in/out coming of the pipes. The black lines are in correspondence of the bendings around the active surface of the absorber. [Source: Arch. G. Paoletti]

4.2.5 Study of the physical interaction with the existing facade

Once the new solar facade is assembled on the existing envelope, they will interact together from the physical point of view.

Between the cassette system and the structure of the existing wall, there could be an air-gap due to the space let free by the sub-structure. Since the element is a solar thermal collector, two different situations occur in summer and in winter-time. In summer, the UST collector warms up the air-gap with the risk to overheat the building indoor spaces, while in winter it could help to create a warm air-cushion reducing the heat losses from the inside towards the outside of the building.

For the design purpose, a parametric analysis has been carried out to investigate the influence of some parameters on the fluid dynamic of the facade system. The solar facade has been modeled in 2D with a finite element method tool, COMSOL [3]. The model consists in the insulation layer behind the absorber and the air-gap, the building insulation and the thermal mass.
Since the metal absorber's thickness (1.5 mm) could be considered negligible if compared to the other layers, the absorber has not been considered in the model. The boundary conditions (BC) concerning the absorber are so transferred to the insulations layer surface S1 (see Figures **??** and **??**).

In the physical model, the heat transfer is due to:

- conduction through the absorber insulation;
- convection heat exchange between cavity surfaces and air mass;
- conduction through the wall layers;
- heat exchange global coefficient between the thermal mass layer and the indoor room.

Table 4.1 lists the physical and geometrical specifications.

Design parameters	Thickness [mm]	Conductivity [W/mK]
Aluminum	1.5 mm	160
Insulation behind the absorber	30 mm	0.0388
Air-gap	300 mm/500 mm	0.0266
Envelope insulation	100 mm	0.0388
Thermal mass	200 mm	0.2550

Table 4.1: Range of design parameters for the set of simulations. The height of the facade is $3000mm$.

The objective was to verify the heat fluxes (q or herein called **F**) through (1) the surface **S2** between the insulation behind the absorber and the air-gap, (2) the surface **S3** between the air-gap and the building insulation, for varying air-gap thickness, and (3) the surface **S5** between the building thermal mass and the indoor space.

Depending on the season, there will be advantages and disadvantages. So the simulations in Comsol have been run under two dynamic configurations (see also Figures 4.4(a) and 4.4(b)):

- natural convection with open air-gap channel for summer;
- natural convection with closed air-gap channel for winter.

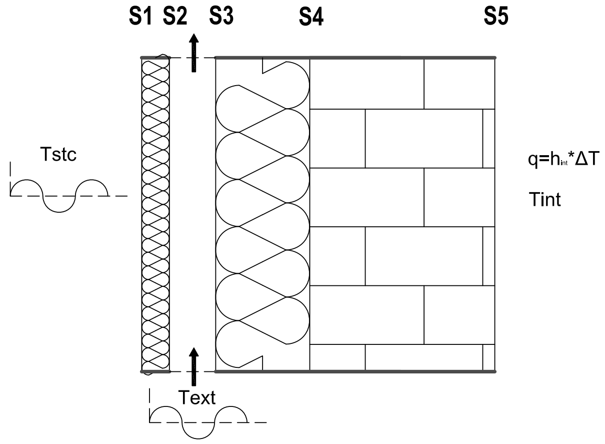
with an air-gap thickness of 30 and 50 mm, which are the minimum technical space due to the presence of the supporting structure of the cassette cladding system.

These two cases, representing respectively a micro-ventilated facade (usually 2 - 3 cm) and a ventilated facade (more than 3 cm) [4], were compared each other.

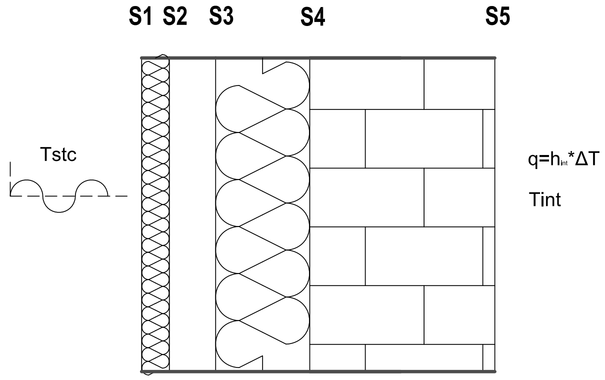
The case without air-gap and with the solar facade added directly on the building insulation would fulfill the study on the physical behaviour, but it was not herein discussed.

Further boundary conditions of the model are defined regarding the temperatures:

- **internal room (S5)**: the flux is imposed with a global coefficient on the internal surface of 10 W/m^{2}K (according to ISO 6946), and a fixed temperature of 20 °Cfor winter and 26 °Cfor summer respectively, without considering internal gains of a building;
- **external environment**: the external temperature is defined throughout a function interpolating temperature values of the coldest 48 hours (winter configuration) and the hottest 48 hours (summer configuration). It was decided to impose the temperature of the UST collector on the external surface of the insulation layer to simplify the model;



(a) Open air channel for the summer configuration



(b) Closed air channel for the winter configuration

Figure 4.4: Boundary conditions for the two configurations, open and closed air-channel corresponding to summer and winter, for Comsol simulations.

- **insulation surface S1**: the temperature (called **Tstc**) of the external surface of the insulation layer is as well given by a function interpolating the average temperature values of the collector absorber in the same coldest and hottest 48 hours.

Both these two interpolating functions of the temperature values are obtained running a simulation in TRNSYS on a simple deck (see section 6.2) with weather conditions of Zurich. Both the values are so depending on the time.

Regarding the boundary conditions, the walls at the top and at the bottom are considered adiabatic. Whereas the boundary conditions on the inlet and outlet flows of the air channel change on the basis of the two configurations, winter and summer are:

(a) **Open air channel configuration – summer**: the interpolated function of the external temperature is imposed on the inlet flow;

(b) **Closed air channel configuration – winter**: adiabatic conditions set on the inlet flow and outlet flow.

Results for summer season: Figures 4.5(a) and 4.5(b) show the temperatures (T S2, T S3, T S5, Text and T_{stc}) and the heat fluxes[1] (F S2, F S3 and F S5) of the surfaces S2, S3 and S5 for the two cases with air-gap of 3 cm and 5 cm in thickness. The variations of the flux of the two cases, through the surfaces S2 and through the surface S3, are not so high. The 3 cm air-gap gives a maximum value F S2 W/m^2 at 11h slightly higher of 9.5% compared to the 5 cm case, due to the higher value of air velocity closed to the surface.

Results for winter season: in winter-time, the differences between the two cases are not meaningful (see Figures 4.6(a) and 4.6(b)). A further simulation was run with an air-gap of 10 cm in thickness but the variation of fluxes and temperature are really low.

In the analysis of the behaviour of the package in terms of time, during the first 24 hours, the exchange energy evaluation is important as well in order to understand how much the heat loses from the collector, and so from the absorber plate, influence a well insulated opaque building wall. Depending on the season, the exchange energy in the package had different

Summer: considering the case of 3 cm of air-gap, the daily energy exchange through S2 surface is +647.47 Wh/m^2, that is +8.27% higher compared to the case of 5 cm. During the night, the exchange energy is −31.39 Wh/m^2, +6.14% lower than that with 5 cm.

The evaluation of the energy exchange through S3 surface is +39.49 Wh/m^2 (for the 3 cm case) and +12.28% compared to 5 cm case. In the night, the energy is −44.67 Wh/m^2, that is +0.89% lower compared to 5 cm case.

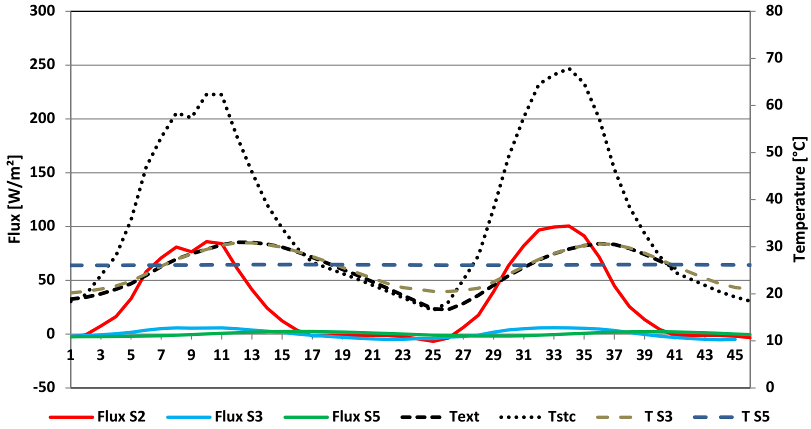
Considering the air-gap of 5 cm, it is so possible to see that during the day the energy flux through S2, S3 and S5, and going towards indoor spaces, is lower than the case of 3 cm. On the contrary, during the night the exchange energy leaving S5 and S3 surface results to be slightly lower than with 3 cm in thickness. A thickness of 3 cm of air-gap seems to be better in the summer season to facilitate the night summer cooling of the building.

Winter: the daily energy exchange through S2 surface is 41.43 Wh/m^2 for both the cases. During the night, the exchange energy for the 3 cm case is −225.72 Wh/m^2, +5.60% higher than that with 5 cm.

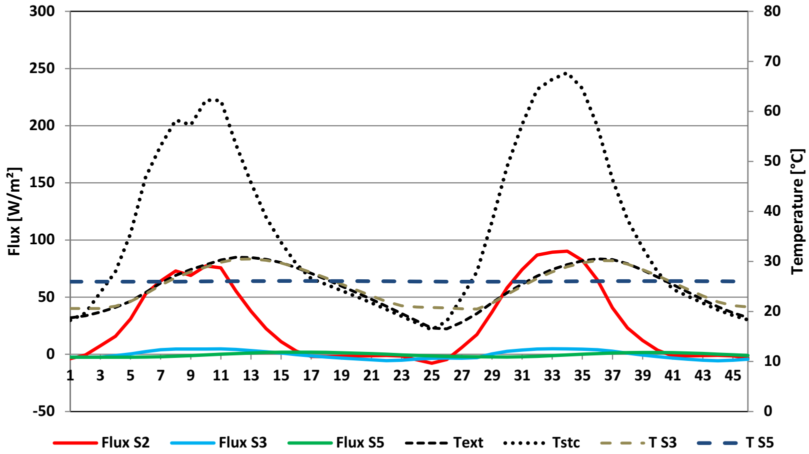
The evaluation of the energy exchange through S3 surface is +31.32 Wh/m^2 (for the 3 cm case) and +3.06% compared to 5 cm case. In the night, the energy is −230.07 Wh/m^2, that is +1.13% higher compared to 5 cm case.

In the winter configuration, the difference in exchange energy leaving S5 surface between the two cases is not so significant, due to the fact that the

[1] The heat flux throughout the layers is considered positive if leaving the outdoor space towards the indoor one and negative if leaving the indoor space.



(a) Open air channel with 3cm in thickness.

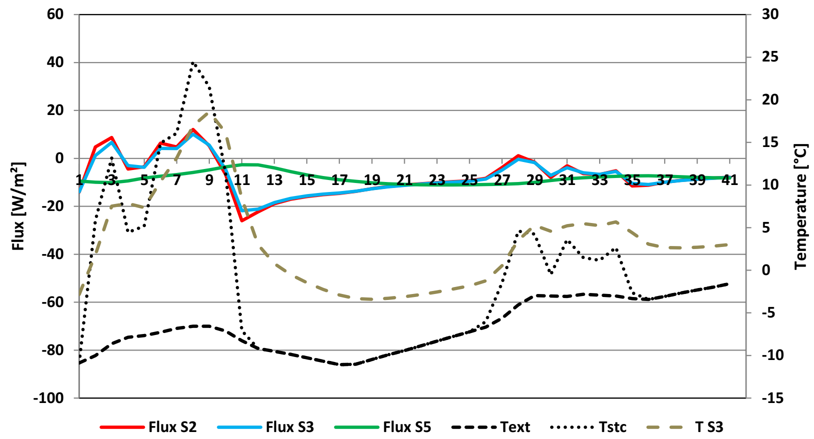


(b) Open air channel with 5cm in thickness.

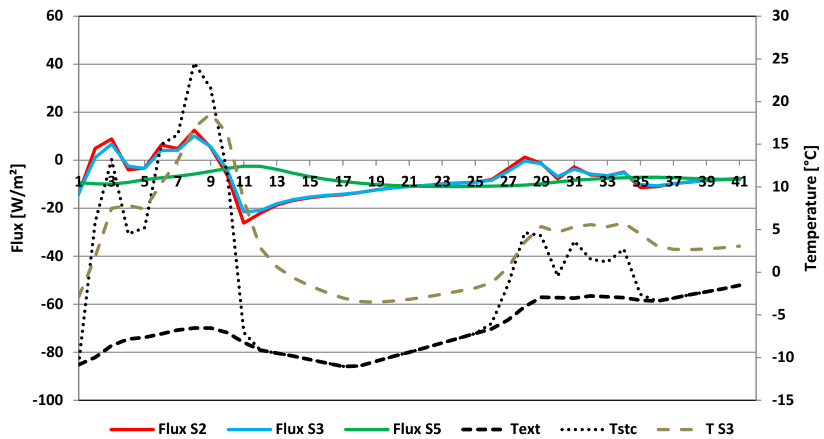
Figure 4.5: Trends of the temperatures and fluxes in correspondence of the surfaces S2, S3 and S5 for the two cases of 3 and 5 cm of air-gap with summer configuration.

air-gap channel is closed.

This preliminary analysis was useful to get a first idea of the possible impact of the air-gap and of the insulation behind the absorber on the indoor comfort, both in summer and winter season. Depending on the air-gap and the building insulation thickness, the behaviour of the package is different in summer and in winter. Once the climate location of the building and the indoor comfort level the designer wants to guarantee are known, the prototype design can be addressed easily.



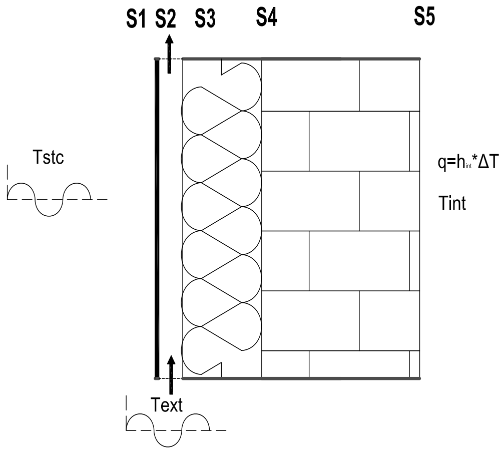
(a) Closed air channel with 3cm in thickness.



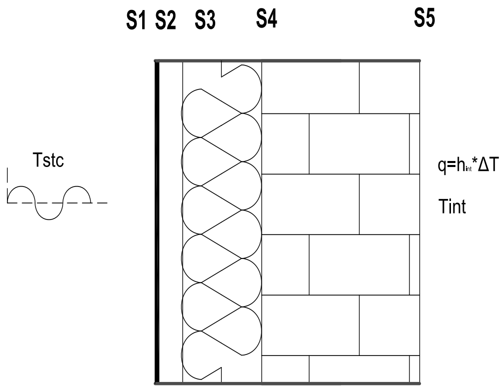
(b) Closed air channel with 5cm in thickness.

Figure 4.6: Trends of the temperatures and fluxes in correspondence of the surfaces S2, S3 and S5 for the two cases of 3 and 5 cm of air-gap with winter configuration.

A further simulation of an **extreme case** was considered in order to evaluate how much the lack of insulation behind the absorber could influence the internal comfort and the fluxes through the package.
Therefore, the facade has been modeled considering just the aluminum layer of 1.5 mm with no insulation behind, an air-gap of 3 cm, a building insulation and a thermal mass of 10 cm and 20 cm respectively (see Figures 4.7(a) and 4.7(b)).



(a) Open air channel with aluminum plate



(b) Closed air channel with aluminum plate

Figure 4.7: Boundary conditions for the second model with the aluminum plate, open and closed air-channel corresponding to summer and winter.

Results for summer season: the maximum value of the flux F S2 is quite higher compared to the other two cases of the first model (see Figure 4.8). F S3 is not so different. F S5 results to have higher variations both in heat loss and heat gain, compared to the two other cases. The flux towards inside is higher compared to the two previous cases, almost double. The heat is stored inside the building in the central hours of the day, while during the night it leaves the indoor space towards outside. The night flux is almost three times higher the fluxes given by the previous two cases.

This effect of free-cooling is quite interesting and it needs to be analysed in-depth as future development.

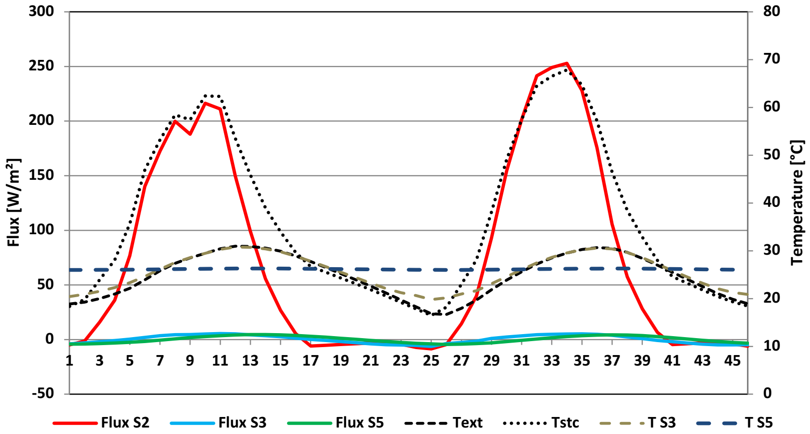


Figure 4.8: Trends of the temperatures and fluxes in correspondence of the surfaces S2, S3 and S5 for the model with the aluminum plate with summer configuration.

Results for winter season: the variations of the fluxes F S2, F S3 and F S5 are wider compared to the two previous cases. Focusing on the S5 surface, the exchange energy values F S5 in the first 24 hours with an air-gap of 3 and 5 cm and 20 cm of insulation are -190 Wh/m^2 and -191 Wh/m^2 respectively. In the extreme case, the matched effect of the hot absorber and insulation layer of 10 cm do not balance the insulation thickness of 20 cm of the previous two cases, since the energy flux through S5 surface is -350 Wh/m^2 (see Figure 4.9).

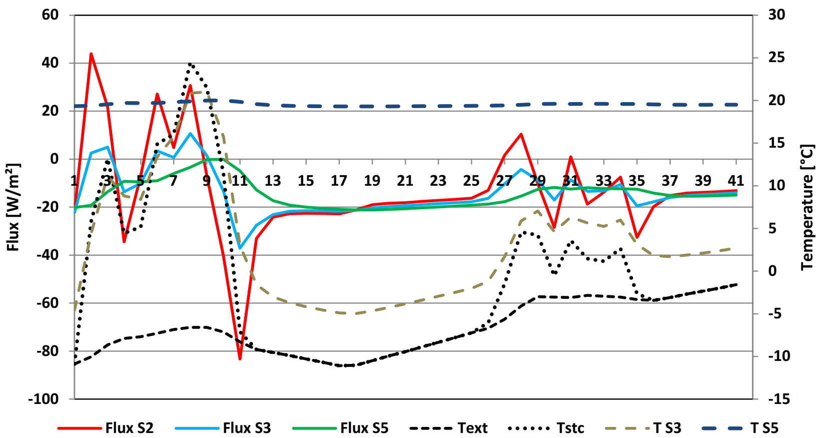


Figure 4.9: Trends of the temperatures and fluxes in correspondence of the surfaces S2, S3 and S5 for the model with the aluminum plate with winter configuration.

The analysis with the FEM software Comsol allowed to investigate the influence of the UST collector facade component when assembled on the existing envelope. Three cases have been investigated, (1) air-gap with 3 cm, (2) air-gap with 5 cm and (3) extreme case with the aluminum plate without insulation behind. They should not be considered as design solutions but as reference cases, useful to understand and to have a first idea of the possible impact of the air-gap and of the insulation behind the absorber, especially in the early phase of conceiving the prototype. Further simulations are needed to achieve a correct prototype design.

Furthermore, an evaluation of the annual balance of the heat fluxes would be more significant in order to understand if the insulation behind the absorber is necessary and how much thick the building insulation should be, 10, 15 or 20 cm.

These results would be useful if implemented in a dynamic simulation of the building in order to evaluate the facade when matched with the building. This could be done considering lumped parameters models. Such a model allows to understand in details the dynamic behaviour of the active facade combined with the whole building as energy system and with the weather conditions as well as to optimize the system, depending on the building loads and the climate of the location, on the indoor thermal comfort and the urban context in which the building is placed.

4.2.6 Assessment of the prototype thermal transmittance

The evaluation of the thermal transmittance of the solar cassette is an important value, since it will be used in Section 6.2 as input of the modeling of the UST collector (type 559).

The calculation has been carried out with the support of the Delphin tool [1].

Two adjacent cassettes are been simulated in steady state conditions for the air, considering an aluminum layer 1.5 mm in thickness and thermal conductivity of 0.0266 W/m.K (representing the aluminum solar collector) and a XPS insulation with a thermal conductivity of 0.038 W/m.K and a thickness of 2 cm and 3 cm respectively. On the external surfaces, a value of resistance of 0.04 and 0.13 m.K/W has been taken into consideration according to the standard UNI6946. Moreover, a distance between the two cassettes is 2 cm.

Considering 3 cm of insulation behind the aluminum layer, the thermal transmittance of the solar element is 1.17 W/(m^2.K). Whereas a layer of 2 cm in thickness gives a thermal transmittance of 1.56 W/(m^2.K) 4.10.

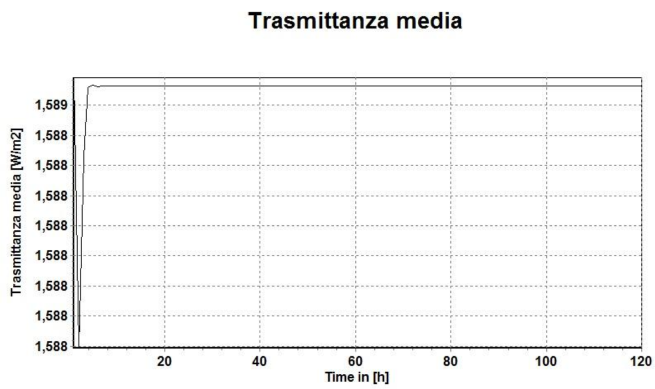


Figure 4.10: Thermal transmittance of the prototype evaluated in steady state conditions with Delphin tool obtained with 2 cm of insulation behind the collector. Source: Ing. P.Baldracchi

The thermal transmittance value of 1.56 W/(m^2.K) has been selected. In order to be in safe conditions, a bigger value of 2 W/(m^2.K) has been considered and set equal to the heat loss coefficient back and edges, as input value requested in the modeling of the UST collector (Section 6.2.2).

4.2.7 Final hypothesis of configuration

The active facade element defined is our hypothesis of design (Figure 4.11). The details are not developed since the hydraulic connections are to be defined with the producer of roll-bond absorber. The set of non active elements such as wall construction, window frame, jointings among cassettes are also to be design together with the facade manufacturer.

The basic idea is to build cassette elements which can be individually hooked onto the support structure and independently removed and replaced without disrupting the rest of the facade system. This is particularly useful if single elements become damaged.

Some details regarding the support structure, the vertical upright and the cassette snap hook structure will be proposed in future development phases of the prototype.

Figure 4.11: Final configurations of the prototype. View on the internal side of the unglazed collector with the channels. The external side is flat. The inlet and outlet pipes are not drawn. Source: Arch. G.Paoletti.

4.2.8 The solar facade as part of the energy system of the building

The active facade also has to be connected to the energy system of the building. The energy system can be used to supply hot water for sanitary use (DHW) and for low temperature space heating. Since the UST supplies water at low temperature (maximum 50 ℃), the use of a conventional back-up system (auxiliary heater) is necessary to cover the energy need when the solar energy is not available for a few days, or, when the thermal solar production is not enough. The most interesting application is the use of the UST collector to pre-heat the water in a storage tank used as cold source for a heat pump in order to cover the mismatch between production and building need in the winter season.

Bibliography

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5 Selection of buildings for the solar facade implementation

5.1 Abstract

In this chapter, the results of the analysis of the heat loads for domestic hot water and space heating of some residential and non-residential buildings are presented. As already described in the section 2.3.1, a European building benchmark model to assess the energy consumptions for each typology of building is missing. The DOE benchmark models have been used with the final objective defining two reference buildings matching well the solar facade features considering its modern and technological aspect and the actual building thermal loads.

5.2 DOE buildings simulation with EnergyPlus

In order to individualise the best matching between the building and the solar facade, it is necessary (1) to analyse the heat demand profile of each type of building, both residential and non-residential, and (2) to individuate the proper building for this kind of innovative application, on the basis of the considerations done in the section 2.3.1.

The design and the development of a new technology in the thermal energy field requires a high sampling rate of the heat consumption. Generally, it is sampled every hour and summed for day, month or year consumptions. More specifically, the short period sampling is important for the peak consumption demand. This knowledge allows a proper design and sizing of the building's energy plant systems, and therefore potential economic benefits (preventing oversized expensive designs).

Since in Europe standardized benchmark models are missing, especially for non-residential buildings, the models developed by DOE were very useful to run a set of simulations in Energy Plus in order to estimate the DHW and space heating loads of buildings located in Europe. The American standards are different but the DOE buildings are proposed as new ones so more similar the European buildings, in the specific in the HVAC equipment. Since the interest in these models does not concern the technologies types but rather the constructive typologies, the models were adopted as applicable also for some European non-residential buildings.

Four building models – a high and a low category hotel, a secondary school and a residential building with eight flats – have been investigated through some simulations in EnergyPlus. Three typical European climates have been chosen, in part by analogy with the choice made within IEA Task 26 Solar Combisystem [6] and with that one made in the analysis carried out by Bonhote et al. [5]: **Stockholm** (northern humid continental climate), **Zurich** (humid oceanic with continental influence) and **Rome** (Mediterranean).

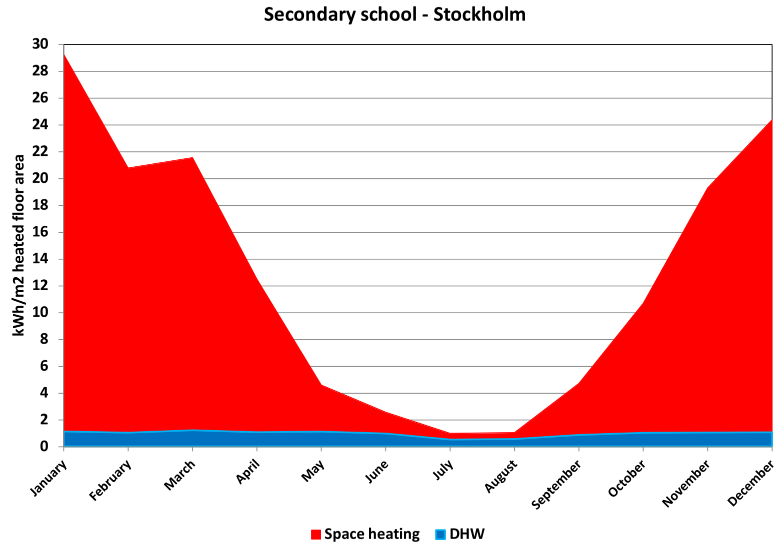
	Latitude (°N)	Longitude (°E)	Height above sea level [m]	Design temperature for SH [°C]
Stockholm - S	59.31	11.93	44	-17
Zurich - CH	47.37	8.54	413	-10
Rome - IT	41.91	12.48	20	0

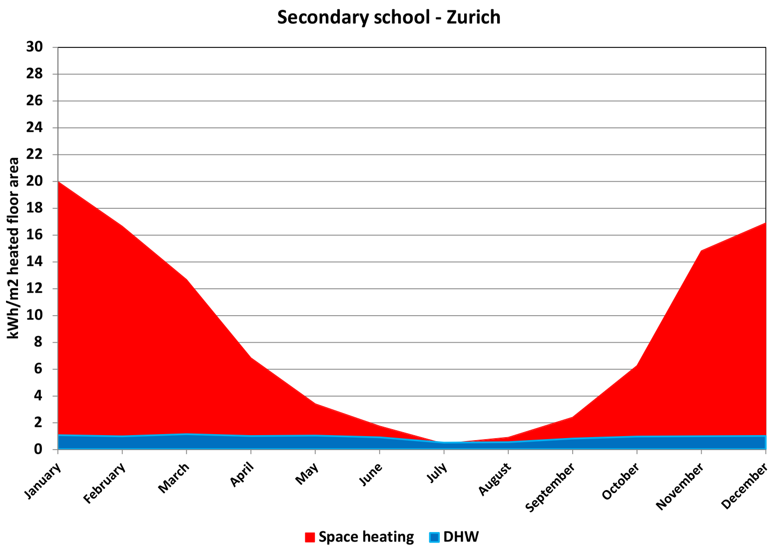
Table 5.1: Data of the European locations.

The next figures show the results of simulations run in EnergyPlus on the five typologies of building (secondary school, high and low category hotel and a multifamily house) in the three European locations. In the tables, the yearly average thermal energy demand for DHW and space heating is reported, whereas the figures show the monthly average loads.

	DHW kWh/m^2	Space heating kWh/m^2	Total thermal energy kWh/m^2
Stockholm	11.41	152.11	163.52
Zurich	10.67	102.67	113.34
Rome	9.48	41.06	50.54

(a) Yearly average thermal energy (kWh/m^2 of heated floor area) predicted by EnergyPlus using the DOE benchmark model of a secondary school for the three European locations.





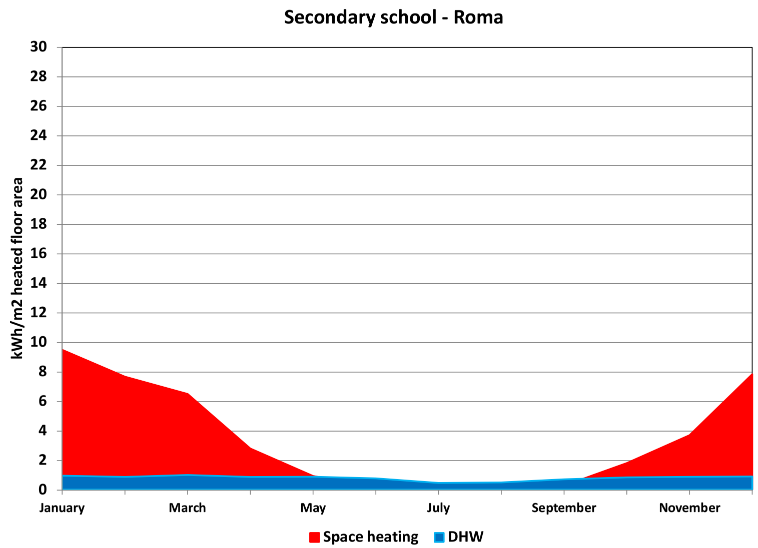
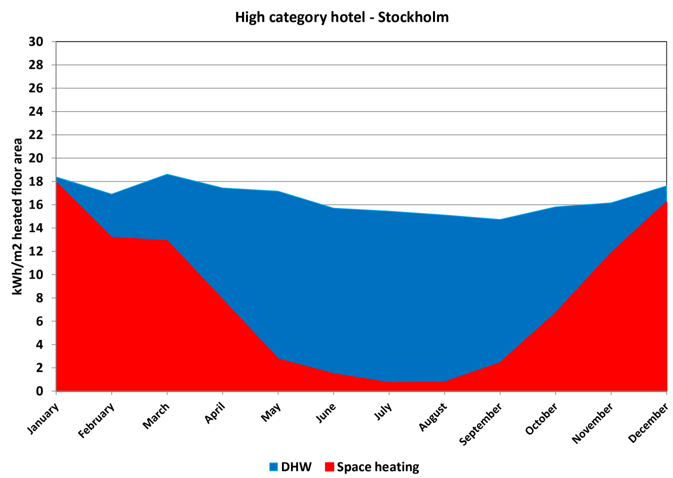
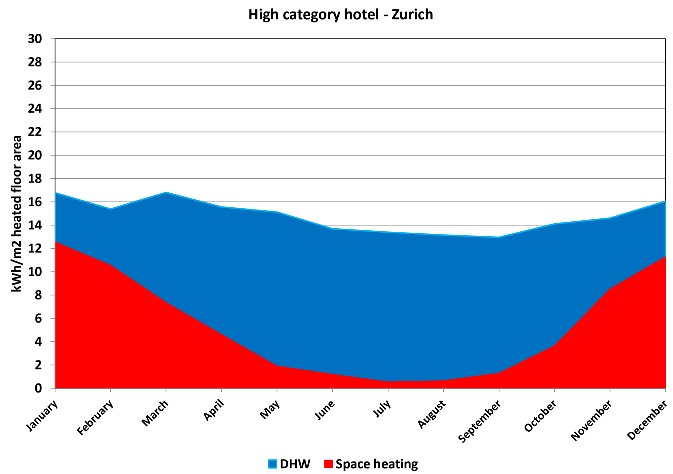


Figure 5.1: Monthly average thermal energy (kWh/m^2 of heated floor area) predicted by EnergyPlus using the DOE benchmark model of a secondary school for the three European locations.

	DHW kWh/m^2	Space heating kWh/m^2	Total thermal energy kWh/m^2
Stockholm	199.13	94.72	293.85
Zurich	177.58	64.15	241.73
Rome	142.95	26.14	169.09

(a) Yearly average thermal energy (kWh/m^2 of heated floor area) predicted by EnergyPlus using the DOE benchmark model of a high category hotel for the three European locations.





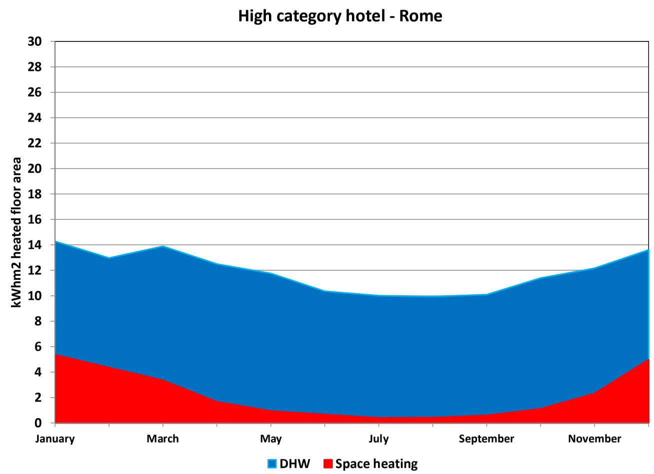
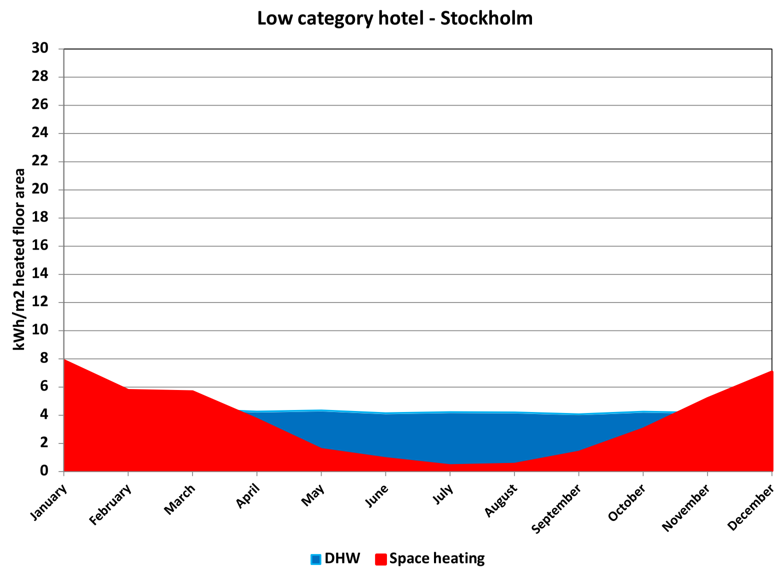
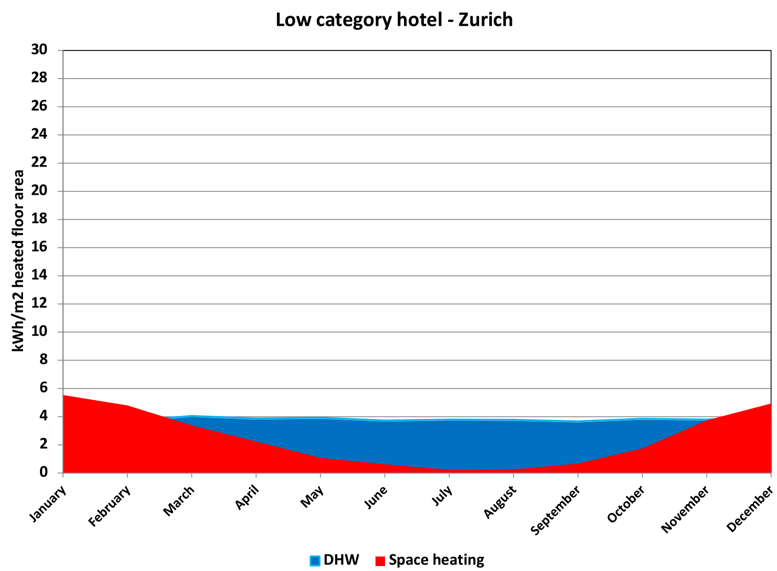


Figure 5.2: Monthly average thermal energy (kWh/m^2 of heated floor area) predicted by EnergyPlus using the DOE benchmark model of a high category hotel for the three European locations.

	DHW kWh/m^2	Space heating kWh/m^2	Total thermal energy kWh/m^2
Stockholm	50.06	42.18	92.25
Zurich	45.32	29.21	74.53
Rome	37.69	12.96	50.66

(a) Yearly average thermal energy (kWh/m^2 of heated floor area) predicted by EnergyPlus using the DOE benchmark model of a low category hotel for the three European locations.





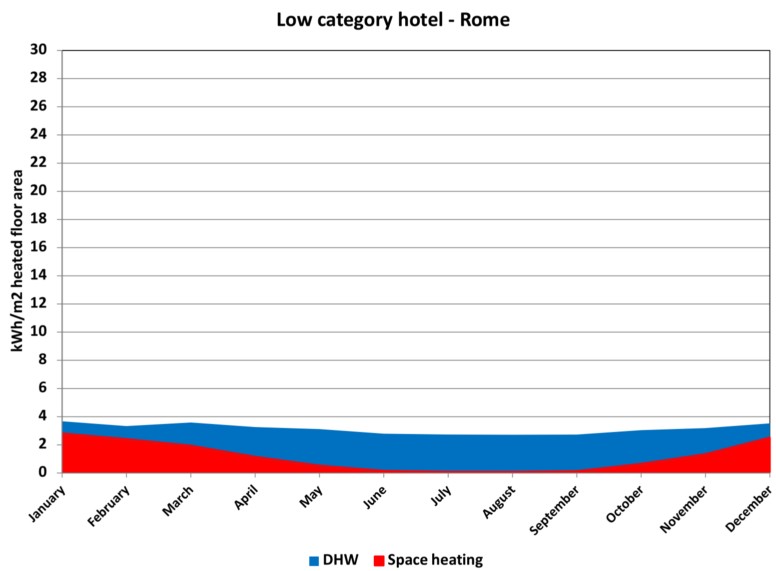
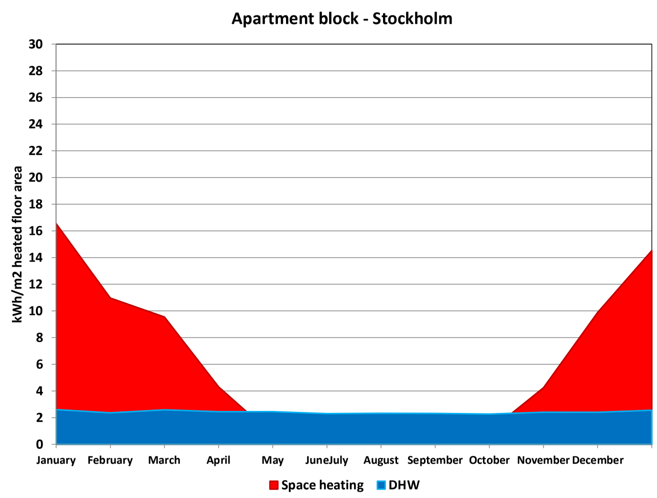
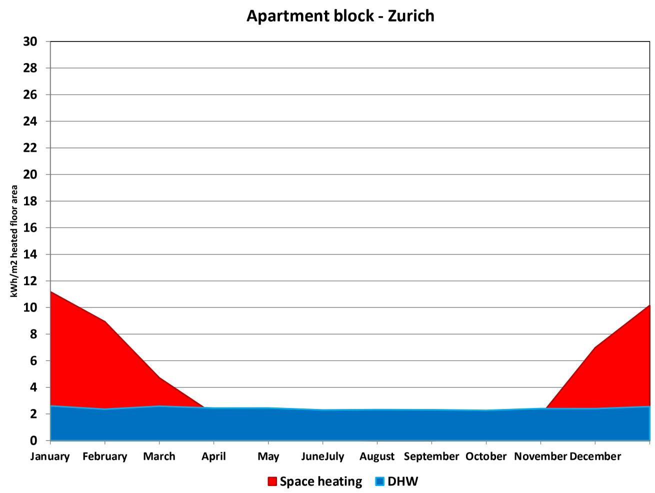


Figure 5.3: Monthly average thermal energy (kWh/m^2 of heated floor area) predicted by EnergyPlus using the DOE benchmark model of a low category hotel for the three European locations.

	DHW kWh/m^2	Space heating kWh/m^2	Total thermal energy kWh/m^2
Stockholm	29.13	76.44	105.58
Zurich	29.00	51.90	80.90
Rome	27.15	14.92	42.06

(a) Yearly average thermal energy (kWh/m^2 of heated floor area) predicted by EnergyPlus using the DOE benchmark model of an apartment block for the three European locations.





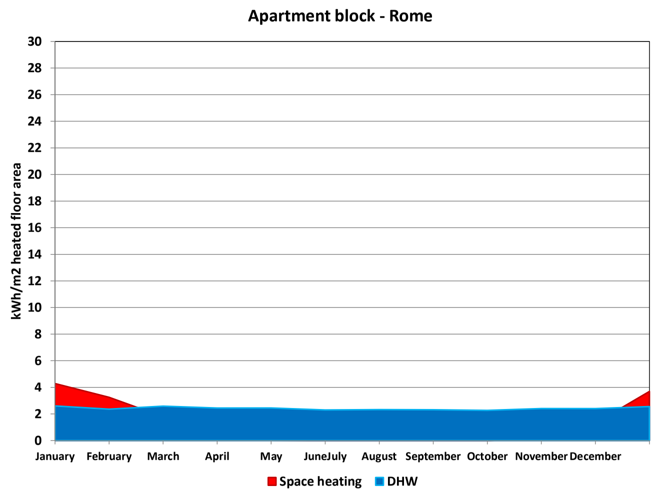


Figure 5.4: Monthly average thermal energy (kWh/m^2 of heated floor area) predicted by EnergyPlus using the DOE benchmark model of an apartment block for the three European locations.

One of the more interesting results of the simulations run in EnergyPlus is about the DHW need profile, since it does not depend as much on the climatic location, but rather on the building end-use. On the other hand, the space heating profile depends on the climate, the typology and the use of the building.

Regarding the thermal energy need amount, **hotels** are the buildings with relatively high demand. In this case, the heat demand depends on the size and on the category of the hotel, the number of beds, the common use areas and if the hotel offers restaurant, laundry services and sport facilities. One more important factor is the behaviour of the occupants which has a direct effect on the energy consumption - especially on DHW demand, as reported in the analysis by Santamouris [3]: "hotel building occupants are not energy conscious and tend to be unusually reckless in their energy use habits. This could be probably attributed to the prevailing feeling that the temporary presence of hotel residents, over a few days at a time, has no direct impact on the annual building operation". This behaviour is confirmed by the comparison of the DHW demands of a high and a low category hotel. Figures 5.2(b), 5.2(c), 5.2(d) and figures 5.3(b), 5.3(c) and 5.3(d) show the different profile of termal energy load respectively for the high and for the low category hotel, this last providing clients with fewer services.

Figures 5.1(b), 5.1(c) and 5.1(d) show the simulated energy consumption profile for the **school** model. In this case, the energy demand for DHW is quite low, especially in summer when the schools are closed. There is so a mismatch between energy demand and energy production. The thermal energy demand for space heating is not as flat during the year as that of the hospital building.

As last, some simulations on a **multifamily house**, composed of 8 flats, have been carried out in order to compare the results with the non-residential stock loads. The monthly DHW demand of this building is relatively constant during the whole year, whereas the space heating load profile depends on the behaviour of the occupants. Since it is not a public building, the occupants can decide to start later or stop sooner the heating period.

5.3 Selected buildings: multifamily house and low category hotel

The unglazed solar system is an innovative product coming from the merging of two different technologies and providing the double function of covering the building facade and producing hot water.
This technology requires to be matched with the proper building typology considering both aesthetic and energy aspects.

1. **Aesthetic aspect**: the unglazed STC requires the facade a pretty modern aspect, therefore not all the typologies of building can accept this product.
   The non-residential buildings get potentially well with this technology, even if a residential building could as well be matched well with, in accordance with designer and user communication wishes to give a modern expression and character to the facade.

2. **Energy match**: the solar application must contribute to cover the yearly heat demand, avoiding as much as possible overproduction in summer and miss match in a shorter interval. The main target is firstly the supply of hot water for domestic use and, once this is satisfied, to cover as well the demand for space heating at least in part.

Among the buildings analysed in the previous section 5.2, the low category hotel and the multifamily house lend themself well for the implementation of this modern solar facade component, since (1) they can be renovated with a modern stylish alternative to conventional building facade designers, (2) their thermal loads for DHW are quite constant during the whole year and not so high and (3) the multifamily houses are the buildings typology more diffuse.
This selection does not mean that this technology goes well only with these typologies of building, instead it can be matched with every kind of building demanding a monthly quite constant thermal energy demand for DHW and not so different from the SH one, and requiring a modern architectural appearance. As examples of cassette cladding system for a residential building, figures 5.5(a) and 5.5(b) give an idea of the potential aspect of a residential building.

In order to understand how much surface of the facade is potentially available for the unglazed solar cassettes implementation and thus available to be converted into solar, it is necessary to know the amount of opaque and transparent surfaces of both the buildings, with Southern exposition.
Here following the pictures of the two buildings (figures 5.6(a) and 5.6(b)) and the table 5.2 with the respective values of transparent, opaque and available surfaces for the solar application for the building Southern exposition.

Figure 5.5: Residential building with cassette system, Cable street, London [Source: www.euroclad.ie/applications/residential.asp]. Two cassette elements with different size are emphasized in red.

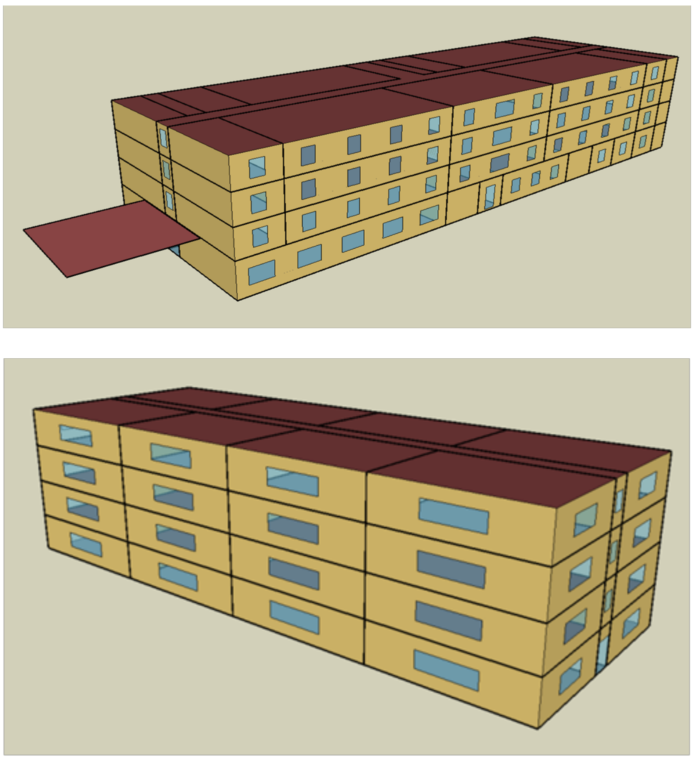


Figure 5.6: Low category hotel (above) and multifamily house (below) pictures of DOE benchmark model.

	Low category hotel	**Multifamily house**
Number of floors	4	4
Heated floor area m^2	4014	3135
Total south facade surface m^2	645.3	554.6
Transparent south facade surface m^2	96.8	83.2
Opaque south facade surface m^2	548	470
Max available opaque facade m^2	300	240

Table 5.2: Data of the low category hotel and the multifamily house of the DOE benchmark model.

5.3.1 Domestic hot water load profile

Water flow rate demand

In the DOE benchmark models, the hourly hot water consumption in a day is given according to the fraction profile of the two buildings (see figures 5.7(a) and 5.7(b)) and on the basis of the peak of hot water demand, which is respectively 2303 l/h for the low category hotel and 303 l/h for the multifamily house [4].

The two profiles look like similar, even if the multifamily house users show to be less regular in their habits, since the two demand peaks in the morning and in the evening are widespread during the day. In the hotel, the hot water is requested in the morning, when the guests have the shower and in the evening, when the guests have eventually dinner at the restaurant.

Delivered cold water temperature

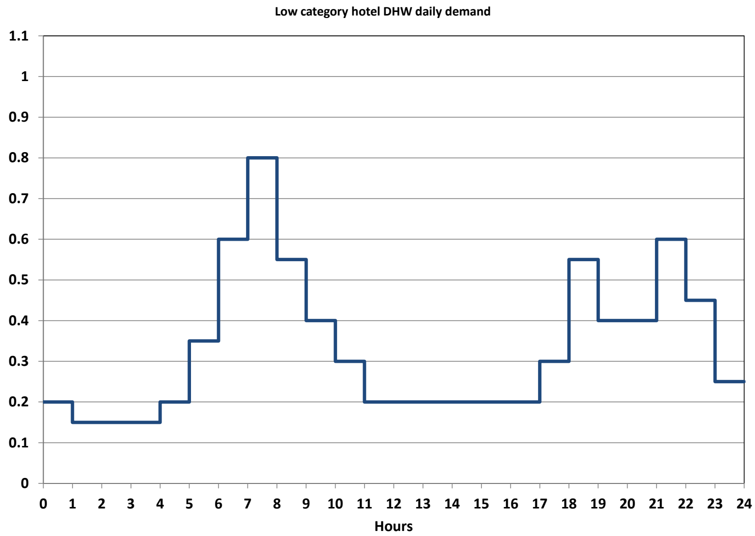
The temperature of water, delivered to the building plant equipment from the waterworks, is an important input for the evaluation of the DHW load. Usually the supplied cold water temperature is a function of climate conditions and day of year. More specifically, the water temperature depends on two value: (1) average annual outdoor air temperature (dry-bulb), T$_{av}$, and (2) maximum difference in monthly average outdoor air temperatures, $\Delta T_{out,av}$.
In this analysis, a constant value of 10℃is assumed for the water mains temperature in order to simplify the calculation, since the results from EnergyPlus simulations are rather needed to have an overview on the loads and to get the heat demand as input in TRNSYS.

Whereas in TRNSYS, used to analyse the overall system energy performances, a sinusoidal function representing the cold water temperature is used, according to the approach chosen in Task26 [6], and is defined by the following Equation 5.1:

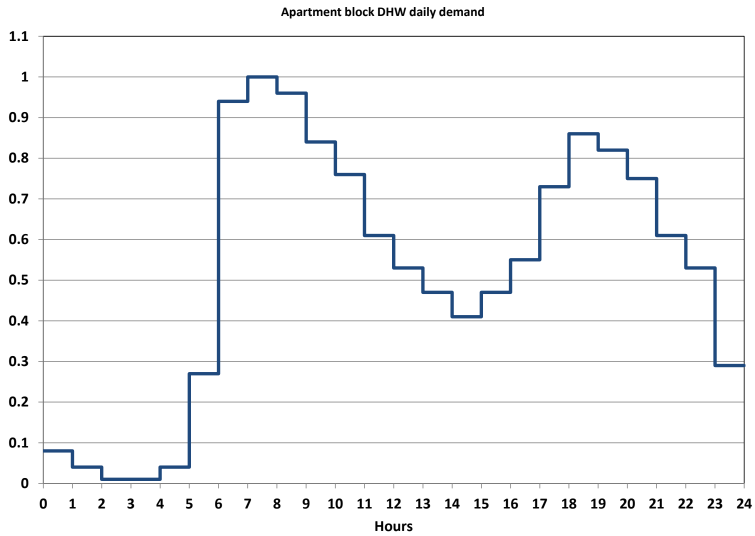
$$T_{CW} = T_{av} + \Delta T_{sh} \cdot sin \cdot \left(\frac{360 \cdot Time + (273.75 - d_{off}) \cdot 24}{8760} \right), \tag{5.1}$$

where 1) T_{CW} is the temperature of the supplied cold water in ℃; 2) T_{av} is the yearly average cold water temperature in ℃; 3) ΔT_{sh} is the average amplitude for seasonal variation in K; *Time* is the hour of the year (an internal value used in TRNSYS); d_{off} is the time-shift parameter (day of the year with maximum temperature).

For the reference locations, these values are listed in the following Table 5.3 [6]:



(a) Low category hotel hourly DHW profile in a day.



(b) Multifamily house hourly DHW profile in a day

Figure 5.7: Hourly DHW profile in a day of the two reference buildings.

	T_{av} ℃	ΔT_{sh} ℃	d_{off}
Stockholm	8.5	6.4	80
Zurich	9.7	6.3	60
Rome	15.22	5.9	12

Table 5.3: Data for the sinusoidal function describing the supplied cold water for each locations.

5.3.2 Space heating load profile

The space heating load of the two buildings is obtained by EnergyPlus simulations as well.
For each of the three European climate locations, EnergyPlus provides the hourly sensible heating load in Watt of every thermal zone of the hotel and the multifamily house. As first simplification, there are taken into consideration only the thermal zones more frequently used by the occupants, e.g. guest rooms for the hotel.
As second simplification since there is no interest to analyse each thermal zone in details, the building model as unique thermal zone is used, so heating loads for each zone are simply aggregated.

In the study of the coupling UST facade system and building energy system, described in the next section 6, the space heating load is considered for a low temperature heating system, that is a radiant floor. In this typology of system, the water temperature is close to the room temperature, whereas in the traditional radiator - heater distribution system the temperatures are between $+50 \div +70$°C. If the heat is distributed under the floor, the temperature of the water can be only $+25 \div +35$°C, providing more energy efficiency and a comfortable indoor climate as the system distributes heat more equally. Low temperature heating systems are flexible as they can use a variety of sources of heat including solar energy.

The renovation action of the building involves the facade as well as the building heating system and therefore the floor slab, with the radiant floor. In fact, the thickness of the floor is increased and this is an aspect to take into consideration in the definition of the room's height.

Radiant floor design

The heating radiant floor has been designed according to the standard UNI EN 1264-2:2009 [1]. In addition to the space heating load obtained by EnergyPlus simulation, further variables are requested for the design: the composition of the floor and the thermal characteristics of the materials, defined in the following table 5.4, the diameter and the wheelbase of the pipes.

	Thickness m	Thermal conductivity W/(mK)	Thermal resistance m^2K/W
Ceramic tiles	0.018	1.200	0.015
Screed with heating system inside	0.075	1.200	0.0625
XPS insulation	0.020	0.032	0.6250
Lightweight screed	0.050	0.120	0.7575
Concrete and mansory floor	0.250	0.330	0.0333
Plaster	0.030	0.900	1.510

Table 5.4: Variables for the radiant floor design.

The pipe inner diameter has been assumed as 16 mm with a thickness of 2 mm and a wheelbase of 15 cm.

Furthermore, the delivery temperature and the flow rate in the heat distribution system are important as well and are calculated in order to answer the space heating demand.

The delivery temperature of the system ($\theta_{delivery}$) is regulated given the outdoor temperature ($\theta_{external}$), with adjusting the heat contribution with the building thermal need in order to guarantee internal comfort. In fact, the building thermal demand increases with increasing of the building heat losses and with decreasing of the external temperature.
For a given minimum outside temperature (θ_{extmin}), the supplied temperature is set to its maximum feasible (by the system) which is in this case 35℃(usually between 30 and 45℃in order to guarantee indoor comfort). This set temperature decreases linearly with increasing outside temperature to an equal temperature of 20℃, chosen for internal comfort (see figure 5.8).

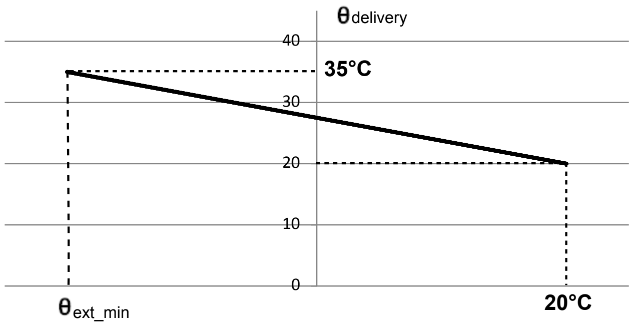


Figure 5.8: Trend of the delivery temperature to the building radiant floor system.

Concerning the water back temperature of the heating system, it is suggested to adopt a temperature drop, between supply and return, below $8-10$ K as a rule [2]. As usually it ranges from 3 to 7 K, the water back temperature is fixed at 5 K less than the delivery one, in order to avoid that some rooms get colder than others.
Finally given the hourly heating load, the characteristics of the floor, the delivery temperature and the water temperature drop of the heating system, the hourly flow rate is evaluated.
The flow rate is chosen as variable and proportional to the needed heat load. In the specific, it ranges between the maximum, corresponding to the peak heat load and zero as showed in the figure 5.9.

This preliminary analysis have been carried out to get the energy thermal loads of the two selected buildings (low category hotel and multifamily house) in three different climate locations (Rome, Stockholm and Zurich), using the available DOE building benchmark.

The hourly DHW and SH loads will be used in the next section 6 in the

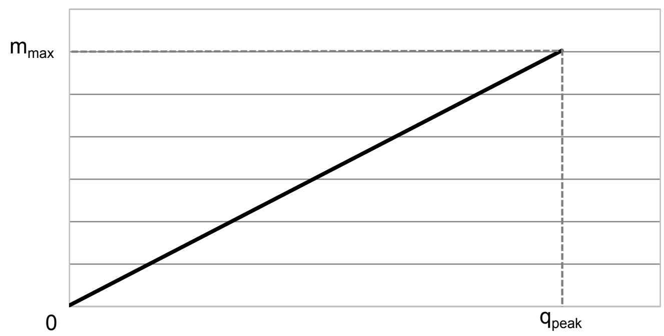


Figure 5.9: Flow rate trend proportional to building space heating load. The maximum flow rate matches with the peak heat demand.

modeling of the energy system to couple with the UST collector facade for both the selected buildings. The modeling is carried out through TRNSYS vers.16.

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6

Energy system modeling

6.1 Abstract

One of the main objective of the present chapter is to analyse the performance of a building energy system including UST integrated in the envelope. In order to carry out the parametric analysis approach, energy simulations tools are used. These simulations support the design choices for the energy systems of BIST to optimize their interactions with the envelope and to reduce the overall energy consumption.

The unglazed STC is combined with the building energy system in order to cover as much as possible the heat loads of the buildings, avoiding as much as possible overproduction in summer and miss match in a shorter interval. The best layout of the water heating system is investigated through dynamic simulations in TRNSYS, considering different values of optimization variables as collector area and mass flow rate.

Firstly, the unglazed STC is coupled with a simple energy system with a storage tank and a back-up. Secondly, a heat pump is added in the hydraulic scheme of the energy system but the sizing and the investigation are part of the future developments.

6.2 Parametric study of the unglazed STC

Unglazed ST collectors represent the simplest and lowest cost typology of solar thermal converters but the high degree of thermal losses implies low efficiency and low output temperature. They can be used in applications such as water pre-heating for domestic use, for low temperature space heating and for swimming pools.

An unglazed collector having a metal absorber has a more interesting potentiality, since it can exchange heat both through convection coupling to the air and through radiation coupling to the sky. Moreover, during the summer night, it can reject heat accumulated during the day in the building and therefore to cool the indoor spaces. In winter, it should exchange heat through diffuse light under a cloudy sky.

The first part of this chapter reports the evaluation of the behaviour of the single unglazed collector through a parametric analysis.

More specifically, the analysis aims:

1. at evaluating temperatures coming out the collectors, in order to investigate how the UST collector exchanges heat with the external environment and under which weather conditions it absorbs and loses heat;

2. at individuating the flow rate-to-collector area giving the best compromise between collector efficiency and outlet temperatures.

The analysis is carried out using Trnsys version 16 and TESS Library2004 [1] to identify the component, typically called type[1], which can properly model the UST collector.

In TRNSYS, there are two types modeling an unglazed STC: type 553 and type 559. The type 553 models an UST collector using the collector efficiency equation approach, the efficiency coefficients are inputs to the model as they often change as a function of wind speed and other parameters. The type 559 models an USTC using a theoretical approach where the user supplies the value of the collector efficiency factor (F'). The algorithms of the models are based on Duffie and Beckman handbook [6].

Since one important aspect of unglazed collectors is the heat exchange with the sky and the air and the absorbance and emissivity values of the absorber surface, it was decided to use **Type 559** instead of the Type 553 because the algorithm of this last one does not implement a calculation of the convective and radiation heat transfer coefficients and therefore of the overall heat loss coefficient of the collector.

6.2.1 Type 559 equation description

In type 559 the user is asked to provide some parameters (length and width of the collector, short-wave absorbance and emissivity of the surface, specific heat

[1] TRNSYS is a solver for differential algebraic equations and specially designed for transient simulations, which incorporates a library with the most common thermal energy systems. TRNSYS adopts a modular structure for solving systems of components where each component is described by a subroutine in the nomenclature used is called TRNSYS TYPE. This modular technique to analyze an entire system as the sum of individual components or systems and the interconnection between them. Each type or subroutine contains one or more models for a system component. [Source: http://aiguasol.coop/en/trnsys-3/]

of the fluid) and input data (inlet temperature and flow rate, ambient temperature, sky temperature, atmospheric pressure, wind velocity, incident solar radiation, collector efficiency factor (F') and heat loss coefficient (U_{back}). The model calculates the collector overall heat loss coefficient (U_L) and therefore the collector heat removal factor (F_R). From these, the outlet temperatures and the heat flow rates as well as the efficiency and the useful energy gain are calculated.

Once the collector heat removal factor (F_R) and the flow rate conditions (m) are known, it is possible to calculate the average plate temperature (T_{plate}), the outlet temperature (T_{out}) and the useful energy gain (Q_u).

The general equation for the useful energy gain is calculated from the Hottel-Whillier-Bliss equation [6], followed by the equations for the average plate and the outlet temperatures:

$$Q_u = \text{Area} * [F_R * \text{absorbance} * G_T - F_R * U_L * (T_{\text{in}} - T_{\text{amb}})] \, , \quad (6.1)$$

$$T_{\text{plate}} = T_{\text{in}} + \frac{Q_u}{\text{Area}} * \frac{(1 - F_R)}{\text{Fr}} * \frac{1}{U_L}, \quad (6.2)$$

$$T_{\text{out}} = \frac{Q_u}{m_{\text{in}} \cdot cp_{\text{fluid}}} + T_{\text{in}}, \quad (6.3)$$

$$U_L = h_{\text{conv}} + h_{\text{rad}} + U_{\text{back}}, \quad (6.4)$$

Where:

Q_u is the energy useful gain in kJ/hr;

$Area$ is the total area of the solar collector array in m^2;

F_R is the collector efficiency factor as fraction;

$Absorbance$ is the absorbance of the collector absorber plate for solar radiation as fraction;

G_T is the total incident solar radiation on the sloped collector surface in kJ/(hr·m^2);

U_L is the overall heat loss coefficient for the collector for losses from the back and edges of the solar collector to the ambient as fraction;

T_{in} is the inlet temperature in the collector array in °C;

T_{amb} is the ambient temperature in °C;

T_{plate} is the average temperature in the collector array in °C;

T_{out} is the outlet temperature from the collector array in °C;

m_{in} is the inlet flow rate in kg/hr;

h_{conv} is the convective coefficient in kJ/(hr·m^2K);

h_{rad} is the radiant coefficient depending on the temperature of the sky in kJ/(hr·m^2·K);

U_{back} is the heat loss coefficient for losses from the collector's back in kJ/(hr·m^2·K);

cp_{fluid} is the fluid specific heat in kJ/(Kg·K);

Within the average plate temperature formula, an updated calculation of the radiation heat transfer coefficient is made (see equation 6.4) and the process is repeated until convergence is obtained.
Under no flow conditions, the useful energy gain is zero and the average plate temperature as well as the outlet temperature are calculated as:

$$T_{\text{plate}} = T_{\text{amb}} + \text{absorbance} * \frac{G_T}{U_L}, \tag{6.5}$$

$$T_{\text{out}} = T_{\text{amb}} + \text{absorbance} * \frac{G_T}{U_L},. \tag{6.6}$$

6.2.2 Trnsys deck description

The parametric analysis of the behaviour of the UST model is conducted using a simple Trnsys deck, as showed in the figure 6.1, and consists in the collector (type 559), a pump with constant flow rate (type $3b$), a weather file reader (type $15-6$), an equation providing the inlet water temperature value and a general forcing function the the flow rate value (type 14).

A control signal switches on the pump serving the Type 559 as unglazed collector field if the solar irradiation hitting the vertical surface is higher than 100 W/m^2. The flow is assumed to be an antifreeze solution of 30% glycol in water.

Since the technical and thermal characteristics of the UST prototype are not known yet, on one side some available data of unglazed solar collectors on the market have been taken into consideration in order to individuate that product which could be closer to the hypothetical characteristics of the prototype ; on the other side, some values are taken from the analysis previously carried out on the interaction with the existing facade (see section 4.2.7) and use them as input for the Type 559.
The input data – which are geometrical size, surface absorbance and emissivity of the absorber as well as heat losses coefficient – are already known on the basis of the hypotheses previously set in section 4.2.7 for the final configuration of prototype (see Table 6.1).

First of all, solar absorbance and thermal emittance are important parameters of the unglazed collector. It was decided to take into consideration the characteristic values of thickness insensitive spectrally selective (TISS) paints used for solar absorbers. Orel et al. [4] proposed some coloured TISS paint

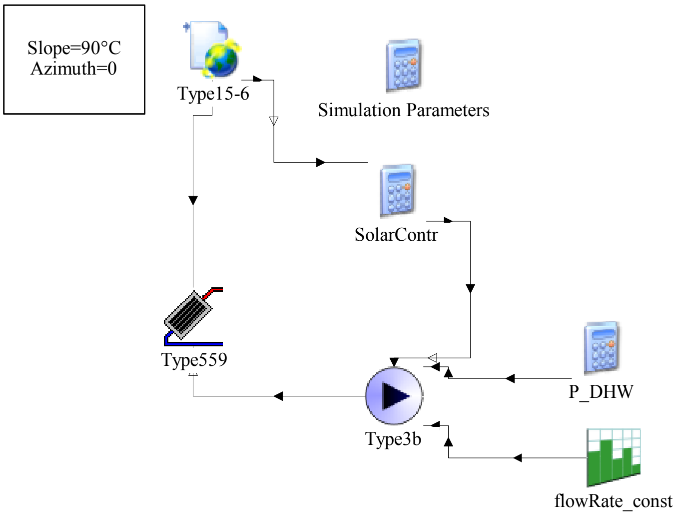


Figure 6.1: Trnsys deck with the UST collectors.

	Value
Surface area $[m^2]$	1
Absorbance coefficient $[-]$	0.77
Emissivity coefficient $[-]$	0.31
Heat loss coefficient back and edges $[W/(m^2K)]$	2
Efficiency factor F' $[-]$	0.84

Table 6.1: Some input data of Type 559.

coatings for unglazed solar facade absorbers in order to meet both the architects' aesthetic needs and the energy efficiency criteria. The value of 0.77 as absorbance and 0.31 as emittance are used in the TRNSYS simulation, and correspond to a blue colour according to the studies carried out by Orel's team [4].

The aim of the study on the UST collector is to investigate the influence of some design parameters and therefore to individuate the flow rate-to-collector area which represents the best compromise between collector efficiency and outlet temperatures. The simulations are carried out on the simple deck with varying area and mass flow rate, in order to evaluate how the efficiency and the outlet temperature change.

Some considerations on the flow rate are here necessary to do. Generally, a high flow rate (m) implies a high thermal energy production of the collectors' field (Q_u) but low quality. In fact, due to the fluid velocity running in the collectors, the fluid is not able to absorb efficiently the solar energy hitting the collectors on the facade. Therefore, the outlet temperatures are quite low. This means that with the same amount of solar radiation, it is not possible to warm up a big volume of water. On the other side, a low flow rate means a reduced thermal energy production but a greater outlet temperature and so a greater exergy, which takes into account not only the quantity but also the quality of energy. At the same time, the pressure drops and the electrical energy consumption for pumps working are reduced.

The simulations have been run in the climate locations of Stockholm, Zurich and Rome. The collector field is placed vertically (slope 90°) and with Southern exposition (Azimuth 0°).

Figures from 6.2(a) to 6.4(b) provide the trend of the solar irradiation on a vertical surface. The external temperature are plotted for the three locations in the coldest day and in the hottest day.

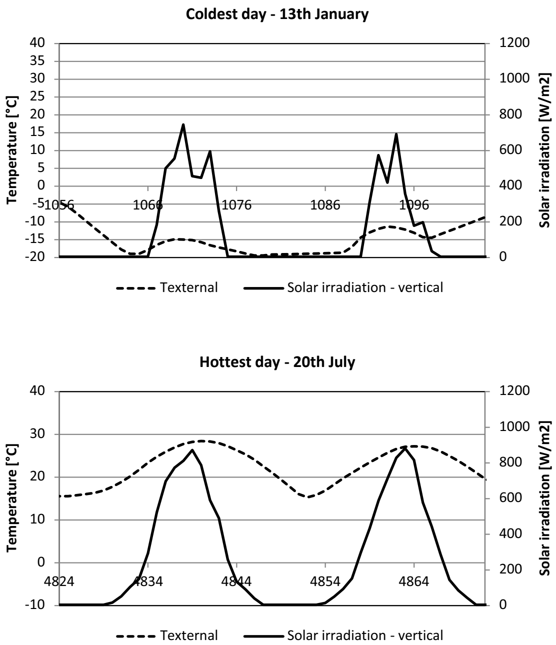


Figure 6.2: External temperature and solar irradiation on a vertical surface in the coldest day (13^{th} January) and in the hottest day (20^{th} July) in Stockholm.

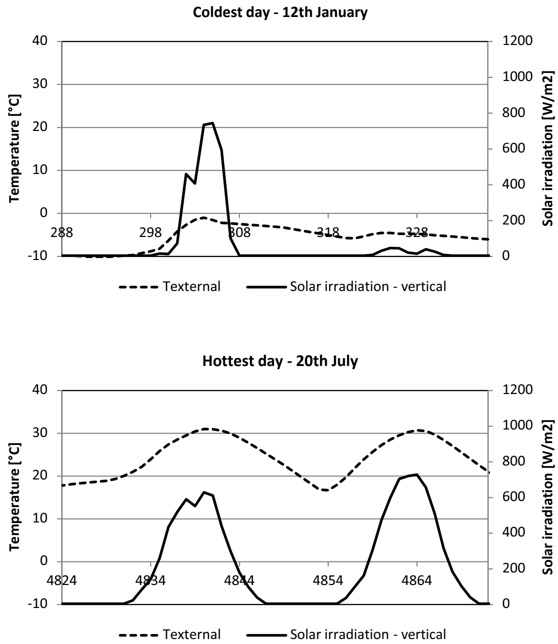


Figure 6.3: External temperature and solar irradiation on a vertical surface in the coldest day (12^{th} January) and in the hottest day (20^{th} July) in Zurich.

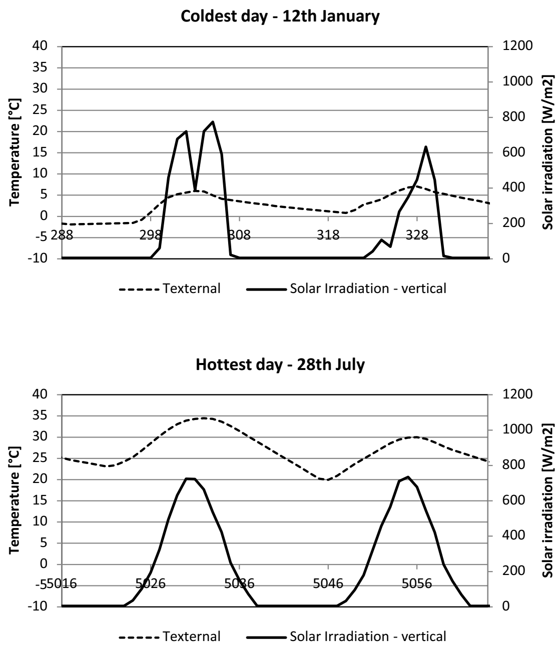


Figure 6.4: External temperature and solar irradiation on a vertical surface in the coldest day (12^{th} January) and in the hottest day (28^{th} July) in Rome.

Results of the parametrization

The first part of the analysis aims to investigate the value of the fluid temperature coming out from the collector, under two conditions: (1) pump of the circuit always working and (2) pump switched on just when the solar irradiation is higher than 100 W/m^2 respectively in the coldest and in the hottest day and during an overcast winter week.

The results, reported for the case of Zurich, show that during the night of the coldest day, if the pump was always working, the fluid goes in the collector with a higher temperature than the external air temperature and the fluid loses heat but it does not reach the balance with the air temperature.

If the pump is controlled by the solar irradiation, the fluid stays in the collector and loses heat towards the external environment, reaching a balance with the air temperature (see Figure 6.5(a)).

In summer nights, if the pump is always working, the fluid exchanges heat and reaches outlet temperatures lower than the air's one. If the pump works with the irradiation (Figure 6.5(b)), the fluid reaches the same temperature of the external air.

The heat exchange with the sky can be positive during the night and this confirms the possibility to use the UST collector to reject heat, when it runs in the summer nights, to cool the building indoor spaces. In winter it exchanges heat also when there is no direct solar irradiation, even if during an overcast week in winter the outlet temperatures do not go up 20℃(Figure 6.5(c)).

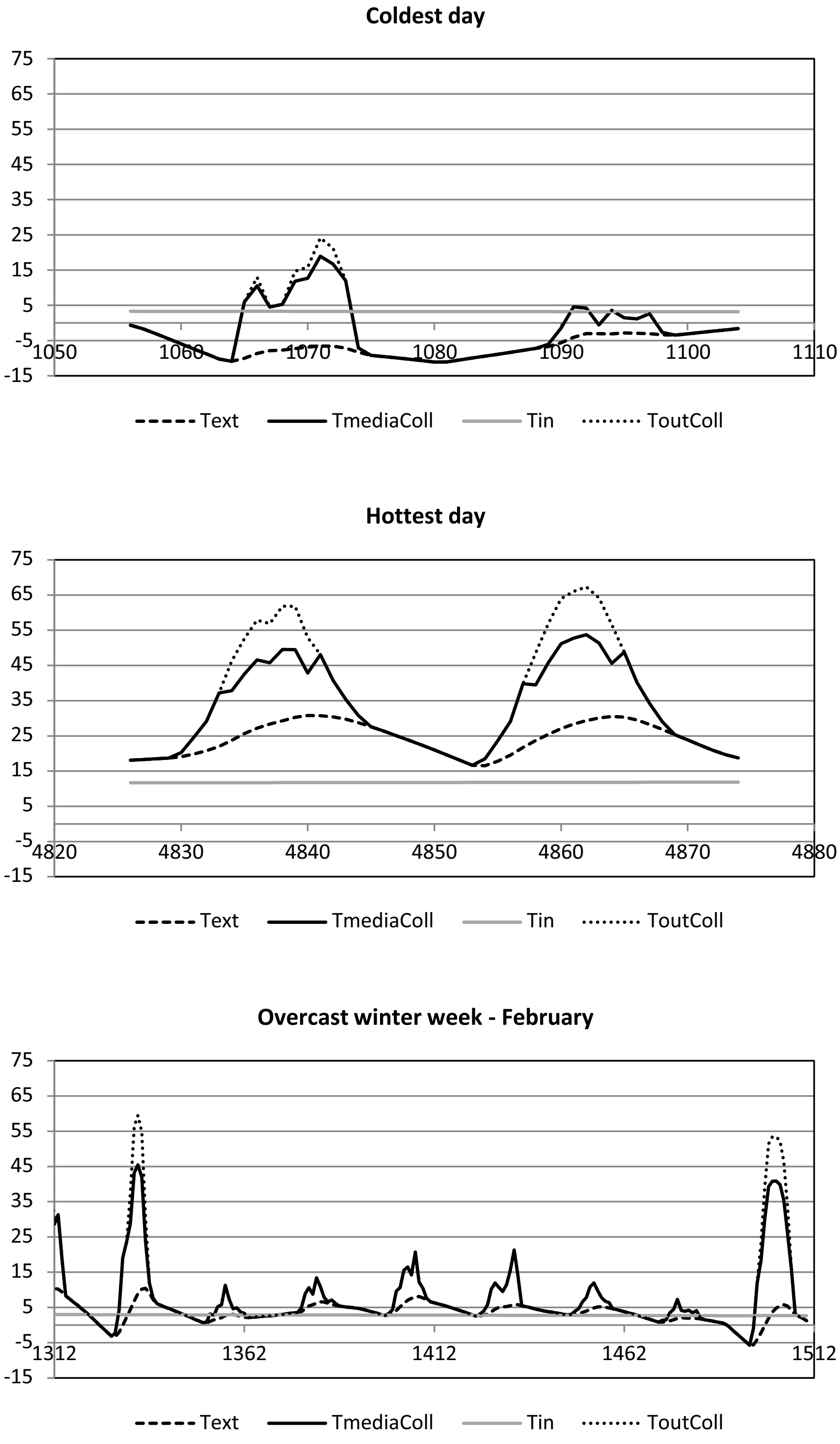


Figure 6.5: Average temperature of the collector in Zurich $T_{mediaColl}$, that is T_{plate}, T_{ext} the external temperature, T_{in} the inlet temperature of the collector, $T_{outColl}$ the outlet temperature of the collector. Above during the coldest day, in the middle the hottest day and below during an overcast winter week.

Moreover, the parametrization analysis aims at evaluating the collectors field's hourly and monthly thermal energy production as well as the fluid outlet temperature. The simulations are run with different values of collector areas (A_{tot}), depending on building available facade surface, which are 300, 200, 150, 120, 80 and 60 m^2, coupled with different values of flow rate, 1000, 5000 and 10000kg/hr, and with a southern exposition.

The results has showed out firstly that the collector thermal energy production and the efficiency are strongly correlated to the mass flow rate, whereas the collector area has a great effect on the temperatures.

The results concerning the efficiency value and the outlet temperature for Stockholm, Zurich and Rome are plotted in the Figure 6.6 for Stockholm, Figure 6.7 for Zurich, Figure 6.8 for Rome. The values of efficiency and temperature are referred at 12 am of the coldest day, and at 12 am of the hottest day for each location respectively.

The efficiency coefficient has been calculated in the equation 6.7 as:

$$\eta = \frac{Q_{sun}}{Irr \cdot A_{coll}}, \tag{6.7}$$

where: Q_{sun} is the useful energy gain of collectors field; *Irr* is the solar irradiation hitting the facade and A_{coll} is the collector area.

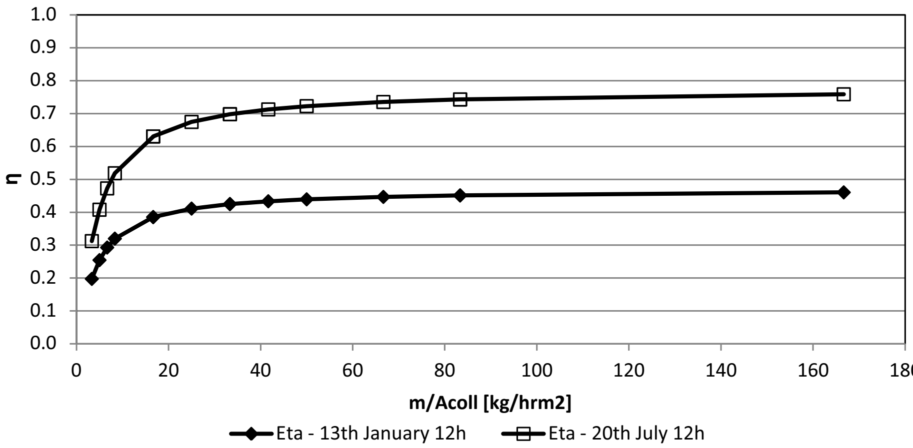
The next figures plot (1) the values of the collector efficiency and (2) the values of the outlet temperature at 12 am in the coldest and in the hottest day with varying of the flow rate-to-collector area, or specific flow rate, for the three locations, Stockholm, Zurich and Rome.

In Figure 6.6(a), 6.7(a) and 6.8(a), it is possible to see how much the specific mass flow rate is correlated to the efficiency coefficient up to 40 kg/(hr.m^2), while there is no significant increase of efficiency with values higher than 60 kg/(hr.m^2).

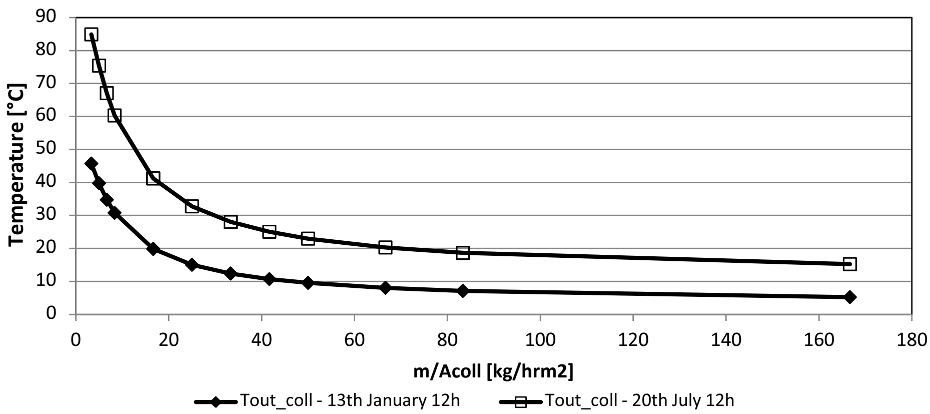
Since the objective is to have a good balance between (1) a useful energy quantity collected by the solar collectors and (2) outlet temperatures as high as possible, values of flow rate-to-collector area higher than 40 kg/(hr.m^2) are discarded.

Moreover, in order to have water with high energy potential, high temperatures are preferred compared to the collector's efficiency. As shown in Figure 6.6(b), 6.7(b) and 6.8(b), flow rates-to-collector area less than 10 kg/(hr.m^2) allow having higher temperatures coming out from the collector as well as higher temperature drops. Of course, in warmer European climates, like in Rome, the efficiency as well as the outlet temperatures are higher than in middle and colder European locations, like Zurich and Stockholm.

Hence, this means to consider (1) large collector areas and (2) low flow rates for the following sizing of the energy system when connected to the UST



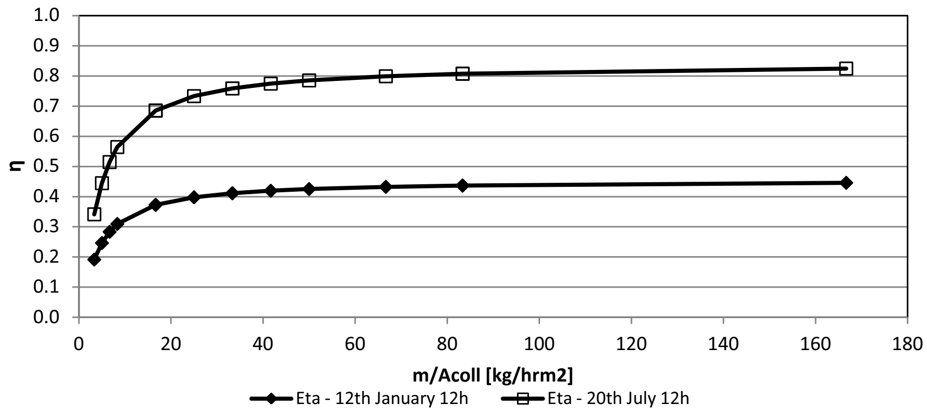
(a) Influence of the specific mass flow rate on the collector efficiency calculated for the coldest and hottest day in Stockholm.



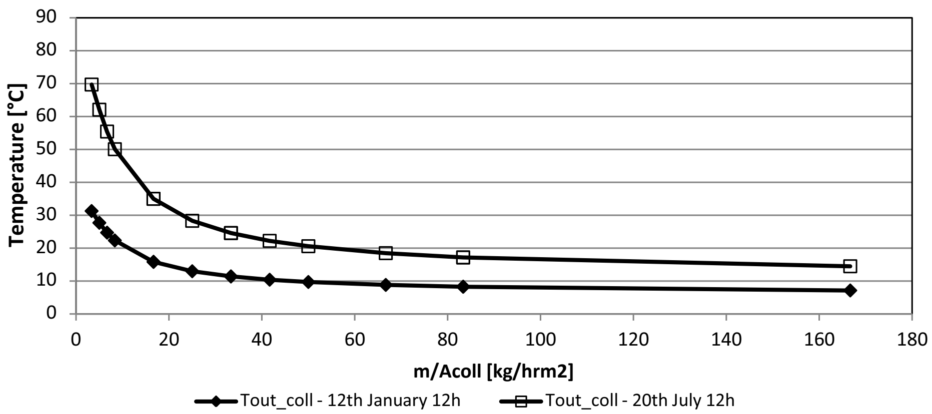
(b) Influence of the specific mass flow rate on the temperature coming out from the collector field calculated for the coldest and hottest day in Stockholm.

Figure 6.6: Collector efficiency coefficient and outlet temperature trends varying the specific mass flow rate between 3.3 kg/(hr.m^2 and 166 kg/(hr.m^2 for Stockholm.

collector, placed vertically.
Since the southern facade of the two reference buildings - 300 m^2 for the small hotel and 240 m^2 for the multifamily house respectively - has a large surface available, one of the possible configuration of the solar collector field could be to cover the overall surface of the facade with UST collector and to vary the flow rate in the range from 1000 to 10000 kg/hr.

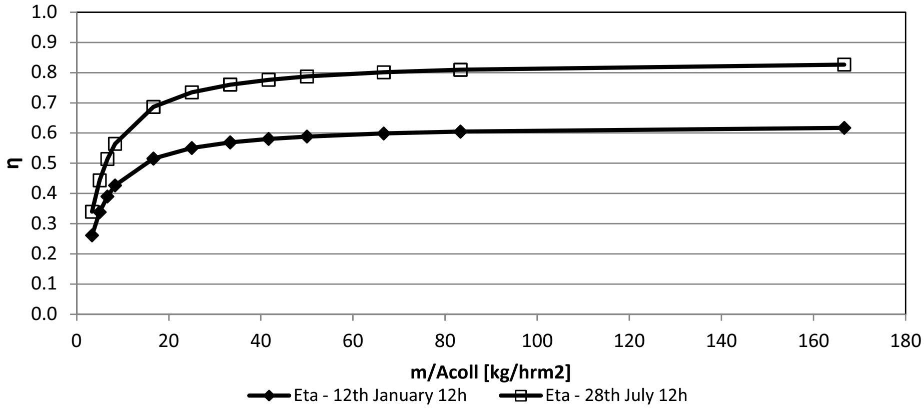


(a) Influence of the specific mass flow rate on the collector efficiency calculated for the coldest and hottest day in Zurich.

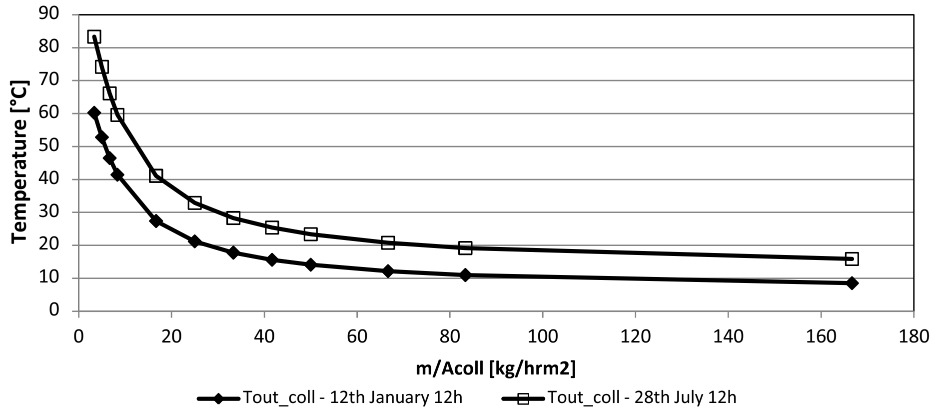


(b) Influence of the specific mass flow rate on the temperature coming out from the collector field calculated for the coldest and hottest day in Stockholm.

Figure 6.7: Collector efficiency coefficient and outlet temperature trends varying the specific mass flow rate between 3.3 kg/(hr.m^2 and 166 kg/(hr.m^2 for Zurich.



(a) Influence of the specific mass flow rate on the collector efficiency calculated for the coldest and hottest day in Rome.



(b) Influence of the specific mass flow rate on the temperature coming out from the collector field calculated for the coldest and hottest day in Rome.

Figure 6.8: Collector efficiency coefficient and outlet temperature trends varying the specific mass flow rate between 3.3 kg/(hr.m^2 and 166 kg/(hr.m^2 for Rome.

The aim of the second part of the study is to individuate the optimum values of flow rate, when the solar collector is integrated in the combisystem of the buildings.

6.3 Study of the UST collector integrated with the building energy system: configuration of a simple combisystem

The second part of the chapter reports the investigation the potentialities of the UST collector when integrated in a building combisystem, for combined space heating and domestic hot water supply, and when all the available facade surface is used.

The objectives are (1) to evaluate the energy performance and (2) to define sizing procedures for the combisystem, in order to decrease the auxiliary heater and increase the solar collectors' utilization.

As a first step, a **simple combisystem configuration** is modeled, as in figure 6.9, and it consists of the following components:

- UST collectors with vertical installation;
- an external heat exchanger;
- a storage tank;
- an auxiliary heater as back-up;
- controllers for the system operation (solar loop and auxiliary heater).

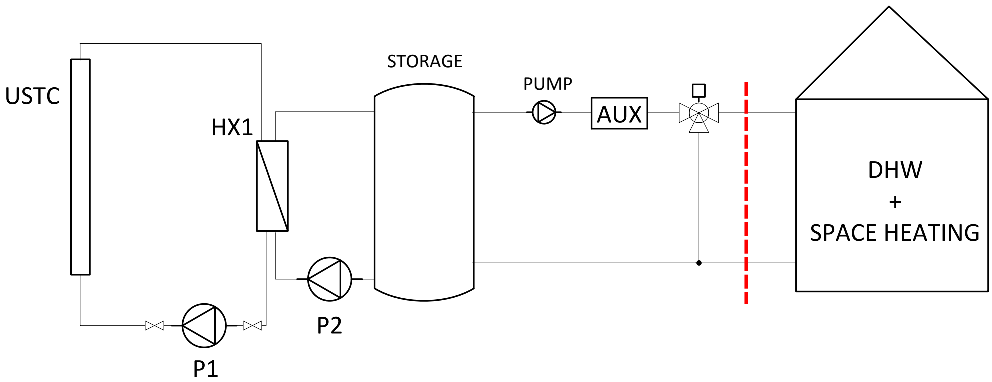


Figure 6.9: Hydraulic scheme of the configuration. The solar fraction and the efficiency coefficient are calculated in correspondence of the red dotted line.

The UST collectors deliver energy, across a counter flow heat exchanger, to the storage tank that in this simple configuration is used for DHW production and for space heating. In case the solar energy is not enough to cover the loads, the back-up system starts to work.

In order to simulate the system, a deck in Trnsys has been developed. All the components of the system (UST collectors, external heat exchanger, storage tank and auxiliary heater) have been modeled and the control strategy implemented.

The deck consists of four main loops: the DHW loop, the space heating loop, the auxiliary loop and the solar one. The storage tank takes place between the solar loop and the building loads.

The figure 6.10 show the TRNSYS deck of the combisystem.

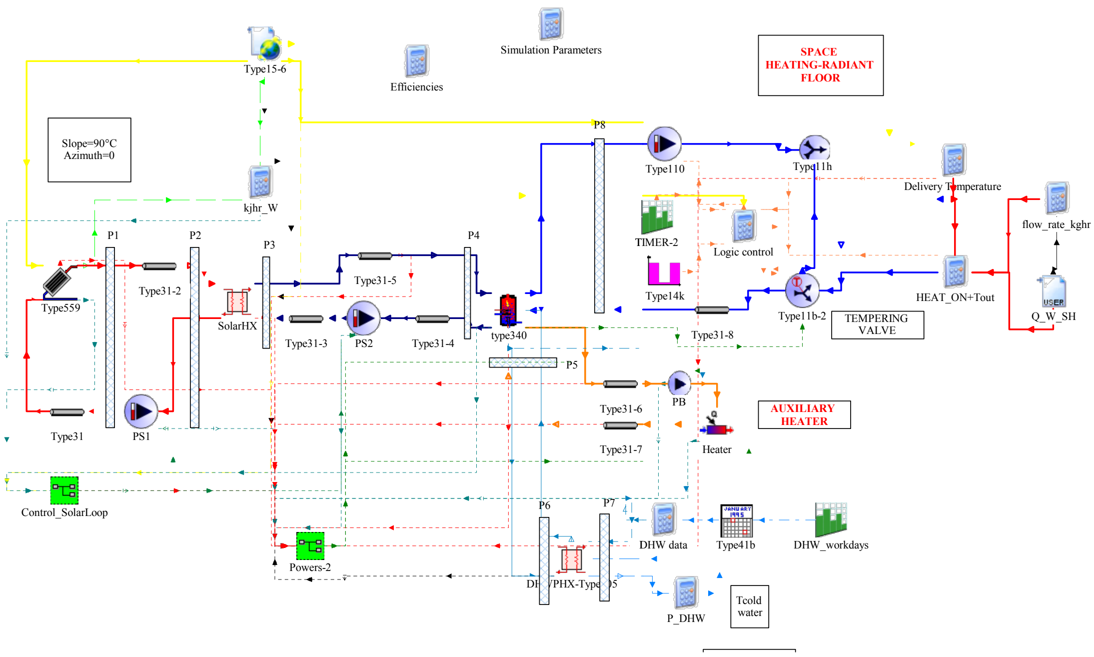


Figure 6.10: TRNSYS deck of the simple configuration of combisystem.

The UST collector field is simulated by means of the type 559. The stratified storage tank is modeled with the type 340. The control strategy is implemented in the solar loop as well as in the auxiliary heater loop.

6.3.1 Space heating loop

The space heating has been sized considering a radiant floor with a delivery temperature depending on the outside temperature and with a heating demand calculated with Energy Plus for each of the two buildings (see section 5.3.2 for details about the radiant heat floor and the dimensioning).

The hydraulic scheme of the space heating system is in the Scheme 6.9 shown, while the corrisponding TRNSYS model is represented in the Figure 6.11.

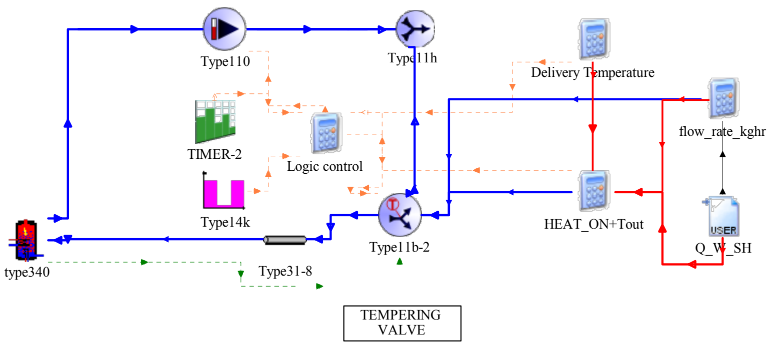


Figure 6.11: TRNSYS model of the space heating loop.

The flow rate coming out of the heating distribution system is sent to a tempering valve.

A tempering valve placed on the return side can send a part of the flow rate, coming out from the floor system, to the delivery pipe to cool the water, coming from the storage tank, when its temperature is too much high.

The mass flow rate directed to the radiant floor goes out from a double port of the storage, i.e. type 340. In order to reach the desired set temperature described in Figure 5.8 in section 5.3.2, the three way tee-piece, type 11*h*, and the tempering valve, type 11*b*, are placed, respectively, immediately after the storage (and the variable speed pump, type 110), and the second one on the returning pipe.

TRNSYS reads the input data, which, for the type 9 and in the two types "*Flow_rate_kghr*" and "*Delivery Temperature*" are the flow rate and the delivery water temperature. For the type "*HEAT_ON+Tout*", a calculation of the outlet water temperature is done considering a temperature drop of 5 K.

In the deck, a logical controller is foreseen in the type "*Logic control*", which calculates the proper value of the set point temperature of the valve and generates the on/off signal operating the pump. This last starts to work on the base of the hourly and seasonal scheduling (between 7-21h during the heating season) and when heating is needed. Concerning the pump working, the flow rate is variable and proportional to the heat load needed. More specifically, it ranges between the maximum, corresponding to the peak heat load and zero as showed in the figure 5.9 in section 5.3.2.

6.3.2 DHW loop

The DHW load profile is obtained by simulations in Energy Plus for each building. The temperature of the cold water is calculated on the basis of a sinusoidal function depending on the outside air temperature of the climate location (for details see section 5.3.1).

The DHW loop is modeled in Trnsys as showed in the Figure 6.12.

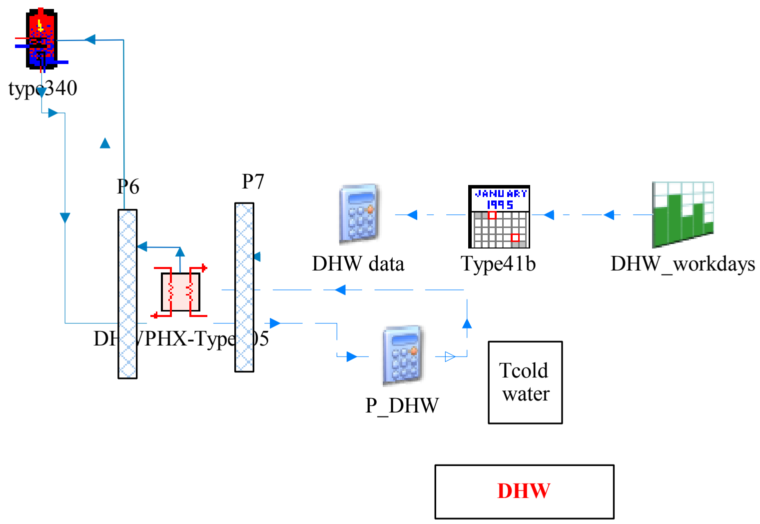


Figure 6.12: TRNSYS model of the DHW loop.

The hourly DHW load fraction profile is listed in the type 14*h* "*DHW_workdays*". In the flow chart of the Figure 6.12, the type "*DHW data*", representing an equation, it is multiplied by the daily peak demand in order to get the liters per hour requested by the building. In the equation "*P_DHW*", the sinusoidal function representing the temperature of cold water is defined according to the equation (5.1) as previously described in section 5.3.1.

Type 805 represents the heart of the DHW circuit. In this type, the primary side flow – between type 805 and type 340 storage – is calculated iteratively until the set point temperature on the secondary side at the given draw-off flow rate or the maximum flow rate on the primary side is reached.
The set temperature for hot water is 45℃.

6.3.3 Auxiliary heater/Back-up system

As it is not reliable to fully depend on the solar energy, the solar combisystem needs a back-up heating system such a gas heater or a heat pump.

The auxiliary heater ensures hot water when the solar energy contribution is not enough, e.g. bad weather, or when there is a high hot water consumption. In these situations, the temperature at the top of the storage decreases to a certain value and the controller operates the switching on of the auxiliary heater.

The auxiliary system is connected in series with the storage tank in the supply loop for building DHW and for space heating, and located before the tempering valve mixing point as showed in the previous Scheme 6.9. The TRSNYS model is illustrated in the figure 6.13.

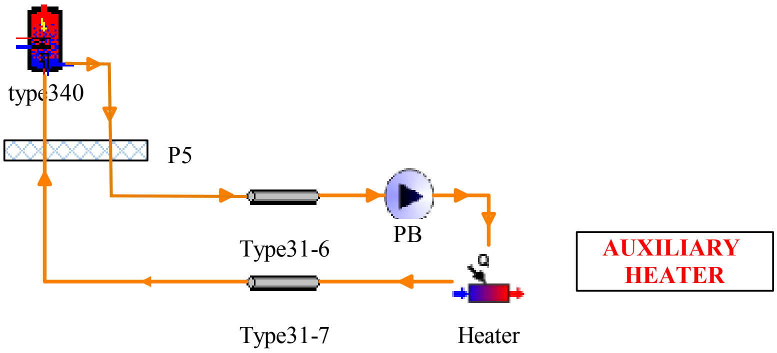


Figure 6.13: TRNSYS model of the auxiliary heater loop.

In the Trnsys model, the auxiliary loop consists of a pump "*PB*" and an electric heater "*Heater*" that keeps the upper part of the storage at a certain temperature level. The heater is switched on in the case that the temperature (monitored by sensor located at the 70% of the total height) is not enough to guarantee a proper working condition.

The pump and the heater are controlled by a signal. This device works in order to keep the temperature within the upper part of the storage buffer at 50°C.

The maximum power of the auxiliary heater is set to 60 kW, to guarantee that the heat loads can always be covered.

6.3.4 Solar loop

The solar loop connects the thermal collectors to the storage tank. It consists mainly of a primary and a secondary solar loop. The primary solar loop is the collector circuit of the system and it is simulated using the type 559, already described in the previous section and representing the UST collectors, the variable pump PS1 with the type 110 and the external heat exchanger (HE) modeled with the type 5*b*. The secondary solar loop is the storage circuit and it is simulated using the solar-HE type 5*b*, the variable pump PS2 with the type 110 and the storage tank, modeled with the type 340. The flow in the primary solar loop is assumed to be an antifreeze solution of 30% glycol in water. In the secondary one for economical reasons the fluid is pure water. The control strategy is implemented in the loop for the operation of the two variable pumps, PS1 and PS2 (see Figure 6.14 for the Trnsys deck and Figure 6.15 for the scheme of the double ports of the storage).
The variable speed pumps PS1 and PS2 are controlled by the same signal, "*SolPSig*". The signal switches on and off the pumps and its value depends on the solar radiation rate hitting the vertical surface and on the difference

of temperature between the outlet of the collector field and the bottom of the storage. If the solar radiation rate on the vertical surface is less than 100 W/m^2, the control signal stops the pumps. If the solar radiation rate is between 100 and 350 W/m^2, the pumps can work between 0% and 100% of their nominal power. Over 350 W/m^2, the pumps can work at the maximum power. The electrical energy comsumption of both the two pumps is calculated as well.

A temperature difference has to be reached simultaneously with the previous condition on the solar radiation rate. With a difference higher than 7°Cthe pumps can start to work, i.e. on= 1, and with a temperature difference less than 2°Cthe signal switches off the pumps, i.e. off= 0. This control signal takes into consideration a hysteresis loop in orde to prevent on/off oscillation around one temperature difference value.

Since the used collector area is considered as large, an external heat exchanger is preferred because it can exchange higher thermal capacities with small temperature degrees.

The storage tank has been modeled with the type 340 and it is provided with four double ports for the inlet and outlet pipes of each loop:

solar loop double port is located at 30% (inlet) and 0% (outlet) respectively of the total height of the storage;

DHW double port is located at 0% (inlet) and 1% (outlet) respectively of the total height of the storage;

Space heating double port is located at 0.5% (inlet) and 0.6% (outlet) respectively of the total height of the storage;

Auxiliary heater double port is located at 0.95% (inlet) and 0.7% (outlet) respectively of the total height of the storage.

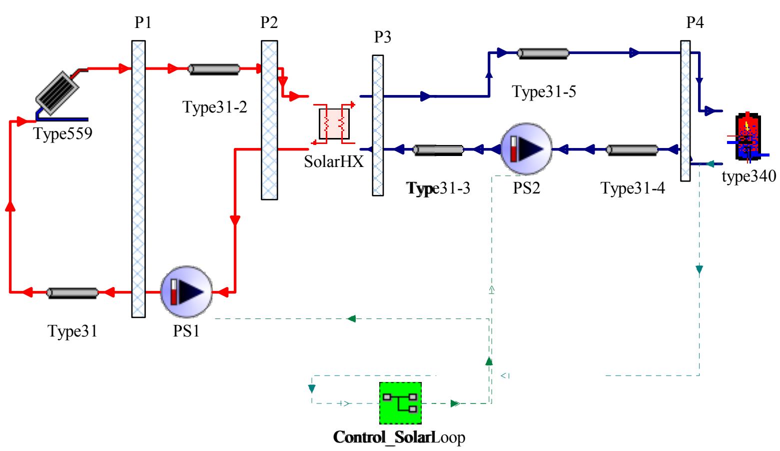


Figure 6.14: TRNSYS model of the solar loop.

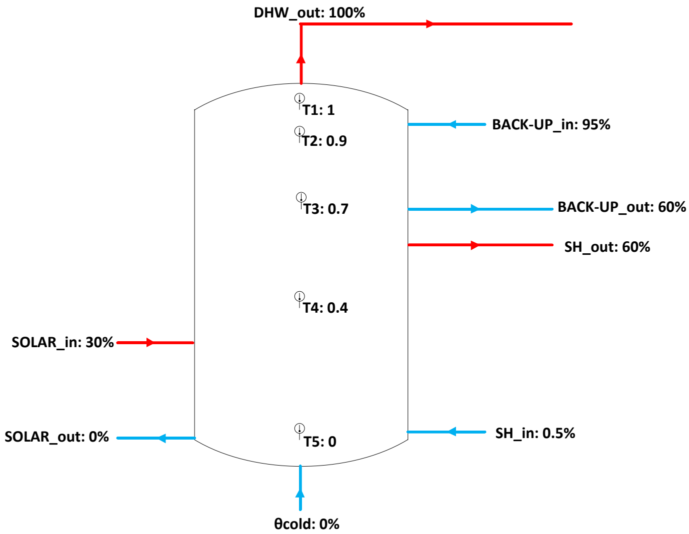


Figure 6.15: Scheme of the double ports of the storage for the inlet and outlet pipes of each loop. The percentage is indicated according to the total height of the storage.

6.3.5 Storage tank sizing

The main purpose of a storage in a system is to overcome offset between solar gain and heat loads.
One of the main aspects is the sizing of the storage, by the fact that we have (1) a low efficient technology (unglazed collectors) and (2) a large collector area installed vertically.

In the literature, some authors propose to size the tank volume giving a ratio in liter per m^2 of collector area: 50 l/m^2_{coll} [3], 50–70 l/m^2_{coll} for solar fraction around 50% and 30–50 l/m^2_{coll} for solar fraction around 25%[5] and 50–100 l/m^2_{coll} [7][2]. These values are valid for more efficient technologies and with inclinations relating to the climate location (for example 50°in Stockholm and 30°in Rome).

Since the UST produce less heat per m^2, a smaller ratio of liter per m^2 is needed because the UST produce less heat per m^2 to achieve the same energy production amount.

The facade system is characterized by low efficiency and low solar energy production if compared with the optimal slope of the ST systems. This means

[2]When the ratio is less than 50 or above 100, the annual and monthly solar fraction, which is the fraction of the total hot water energy that is supplied by solar system, is not so high.

that the possibility to store heat per m^2 of collector area is lower.

On the basis of these considerations, it was decided to carry out a parametrization on the system selecting the storage volume in the range 10–50 l/m^2_{coll} of tank volume-to-collector area ratio.

The overall heat loss coefficients of the tank has been considered at the constant value of 3W/K.

6.3.6 Results of the simulations

Once the combisystem model in Trnsys and all the components are defined, the parametric analysis has been carried out following the study of Hobbi and Siddiqui [2]. The authors used the solar fraction of a solar water heating system as optimization parameter to determine optimum values of design parameters of the system and of the collector, such as collector area, collector mass flow rate and storage tank volume.

They run a first set of simulations in Trnsys varying the collector area with fixed values of tank volume-to-collector area ratio (V_c/A_c) and mass flow rate (m) to estimate the annual and monthly solar fraction and to determine the adequate collector area. Furthermore, they run simulations to determine the effect of the collector mass flow rate on the annual and monthly solar fraction, keeping constant the collector area (A_c) and the tank volume-to-collector area ratio (V_c/A_c). Afterwards, they determine the effect of the tank volume on the system performance for the determined values of collector area and mass flow rate.

This methodology has been adopted in this study to estimate the influence of storage tank volume on the solar fractions and efficiencies (for annual average) of the combisystem, but with different conditions:

1. a different technology is used, that is an unglazed ST collector having a low efficiency compared to the glazed ones;

2. the collectors are installed in the south vertical facade and so an annual solar irradiation reduced by about 30% (compared to the optimal slope of the location) has been considered;

3. a fixed and wide surface area for the UST integration is considered, 240 m^2 for the multifamily and 300 m^2 for the low category hotel.

Energy fluxes across the system have also been calculated in significant points to evaluate the correctness of the simulations (see Figure 6.10, the rectangular boxes from P1 to P8) as well as the performance figures that allow the assessment of the system efficacy.

The solar fraction and the efficiency coefficient are calculated in correspondence of the red dotted line in Figure 6.9 and as reported in the following equations (6.9):

$$SF = \frac{Q_{SUN}}{Q_{LOADS}}, \tag{6.8}$$

$$\eta = \frac{Q_{SUN}}{Irr \cdot A_{coll}}, \tag{6.9}$$

where: Q_{SUN} is the useful energy gain of collectors field less the heat losses of the combisystem (external heat exchanger losses, storage heat losses, heat losses along the system path), Q_{LOADS} are the heat loads for DHW and space heating, *Irr* is the solar irradiation hitting the facade and A_{coll} is the collector total area.

As first step, the flow rate of the solar loop has been observed in the range 1000 – 10000 kg/hr, defined in the previous study. The flow rate of the primary solar loop has been determined in order to have an effectiveness ϵ-NTU of the external heat exchanger (placed between the solar source and the storage tank) around 0.75, since most of the products of water-water heat exchanger on the market, with the same heat exchange area, present this typical value.

A flow rate of 1000 kg/hr has been selected as a proper value for all the three locations and for both the buildings and it corresponds to about 4 kg/(hr.m^2), value lower than 10kg/(hr.m^2), as defined in the previous study.

As second step, the storage tank volume has been varied in the range 4–12 m^3, which corresponds to a storage tank volume-to-collector area ratio between 13.33 and 50 l/m^2, with a fixed and wide surface area and a selected value of flow rate equal to 1000kg/hr.

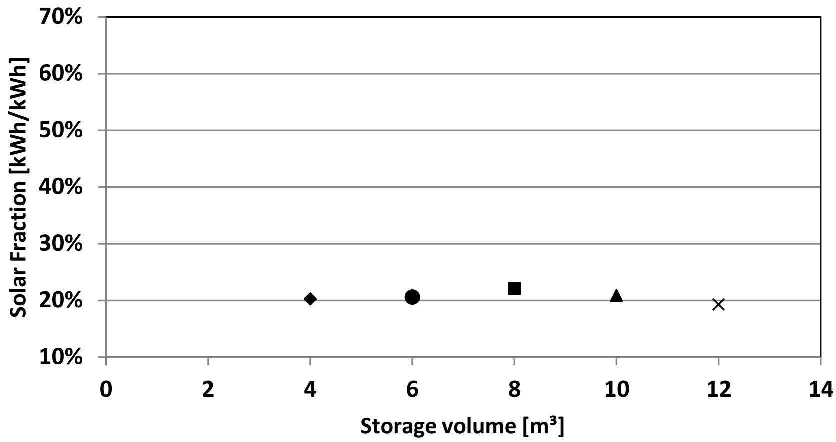
In this range of storage tank volume-to-collector area ratio, the annual solar fraction increases rapidly from 58% to 66% in the figure 6 reported in the Hobbi's article [2].

Following the study of [2], we provide in the following figures the solar fractions and efficiencies (for annual average) plotted versus the storage volume. Figures 6.16, 6.17 and 6.18 provides the results of the Trnsys simulation for the multifamily house case, and 6.19, 6.20 and 6.21 for the low category hotel for Stockholm, Zurich and Rome respectively.

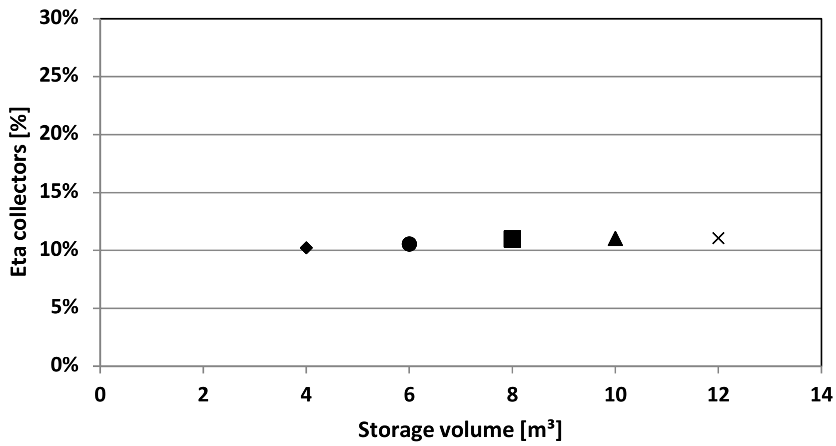
Multifamily house

For Stockholm (Fig. 6.16), the maximum value of 22% occurs around 8 m^3 and there is no big difference among the other values of storage volume, which give an annual solar fractions of 20.5% for 6 m^3 and 21% for 10 m^3 respectively. Regarding the efficiency coefficient, the maximum value is reached in the range 8–10 m^3.

For Zurich (6.17), the maximum annual solar fraction of 26% occurs in the range 8–10 m^3. The volumes of 6 m^3 and 12 m^3 give 24% and 23% respectively. The maximum value of efficiency coefficient is reached above 8 m^3, even if the difference with the other values of storage volume is around 1%.



(a) Annual Solar Fraction value varying the storage tank volume for Stockholm - multifamily house.

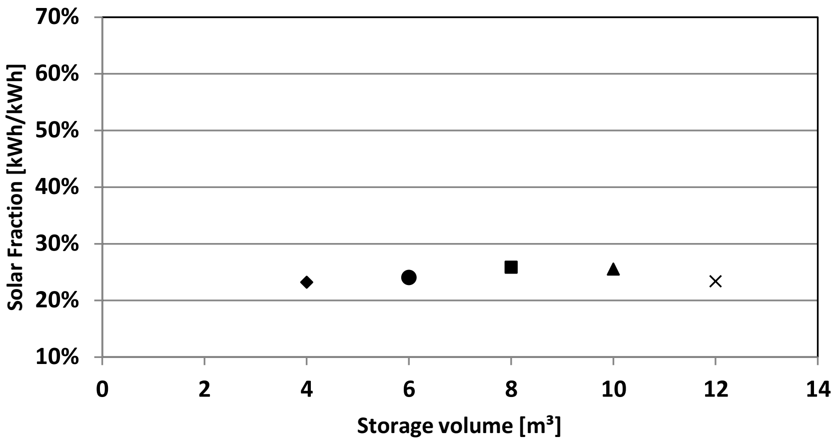


(b) Annual collector efficiency varying the storage tank volume for Stockholm - multifamily house.

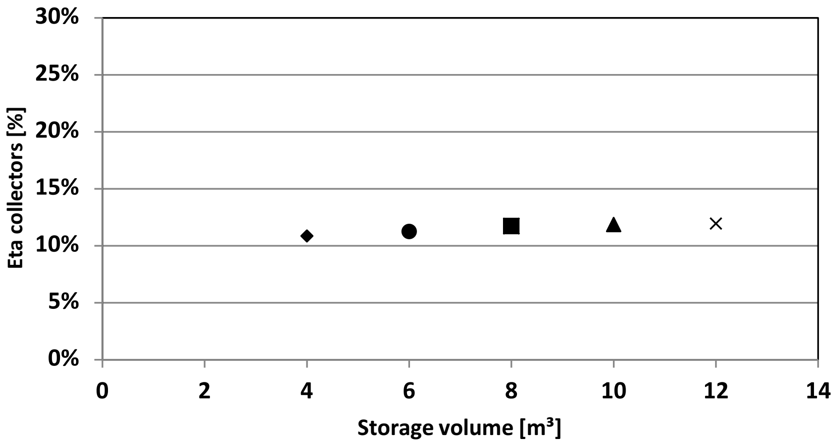
Figure 6.16: Effect of the storage volume on the system performance in Stockholm

In the case of Rome (Fig. 6.18), the highest value of solar fraction is 51% and occurs in the range 8–10 m^3. The difference compared to a 6 m^3 storage volume is 3.6%. The efficiency coefficient shows a constant value of 14% in the range 6–12 m^3 of storage volume.

In order to quantify from the economical standpoint the differences in percentage of solar fraction among the different values of storage volume, it is necessary to know how much one thermal kW per hour produced with gas costs. The authority (AEEG) website reports an average cost of 0.486 euro/m^3. Considering the conversion factor of methane gas of 10.8 kWh/m^3 and a boiler



(a) Annual Solar Fraction value varying the storage tank volume for Zurich - multifamily house.



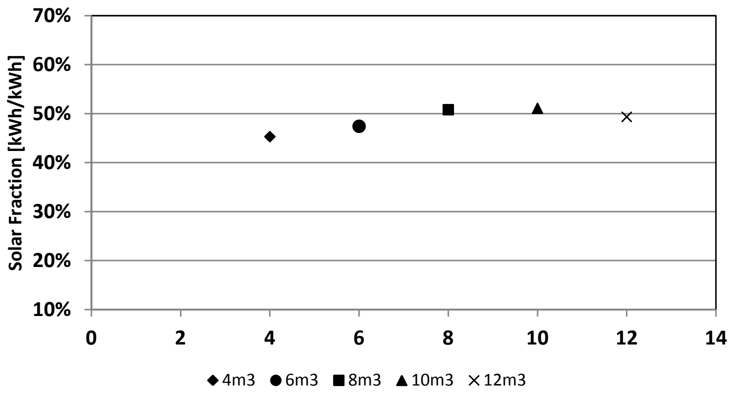
(b) Annual collector efficiency varying the storage tank volume for Zurich - multifamily house.

Figure 6.17: Effect of the storage volume on the system performance in Zurich

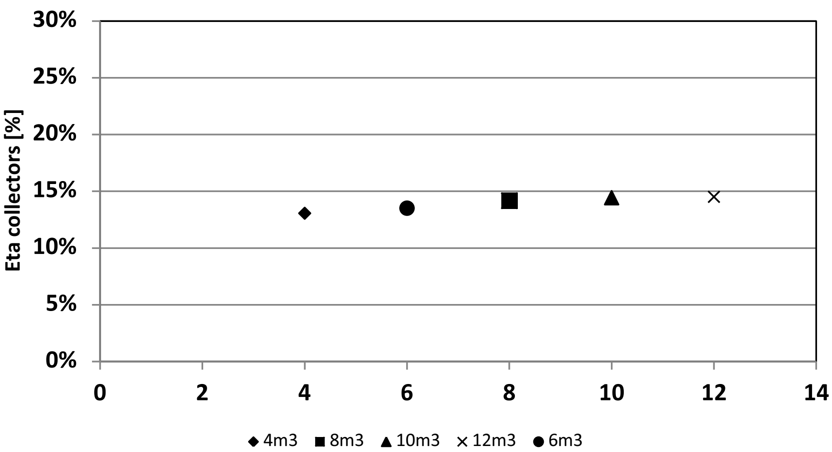
efficiency of 0.9, a fuel cost of 0.054 euro/kWh is acceptable.

In general, the maximum value of solar fraction occurs around 8 m^3, but in case the user would install a volume of 6 m^3 the installation and the maintenance costs will be lower and he will spend around 77 euro (-1%) more every year because of the smaller production. For Zurich, he will spend 135 euro (-2%) and in Rome 211 euro (-3.6%) more. More specificately, in Rome it is not necessary to install a bigger volume per year, with the risk to oversize the system, because of high temperatures. This additional cost for the gas is to be compared to the cost of bigger tanks (and its installation) and higher maintenance cost.

It can safety state 1–3% of solar fraction difference is not meaningfull.



(a) Annual Solar Fraction value varying the storage tank volume for Rome - multi-family house.

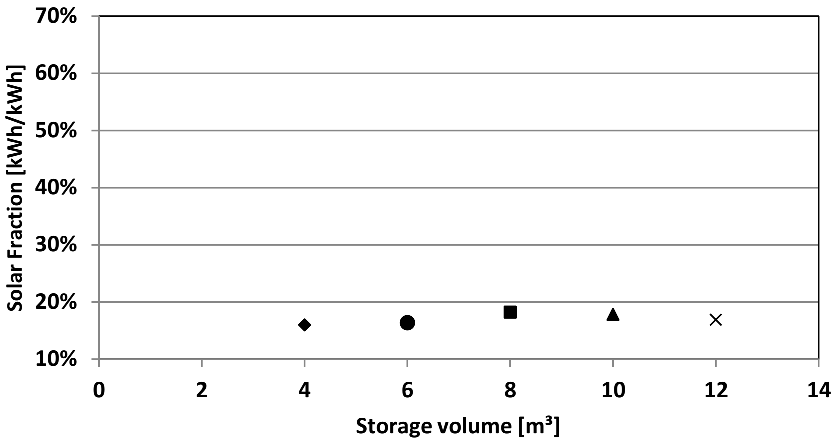


(b) Annual collector efficiency varying the storage tank volume for Rome - multi-family house.

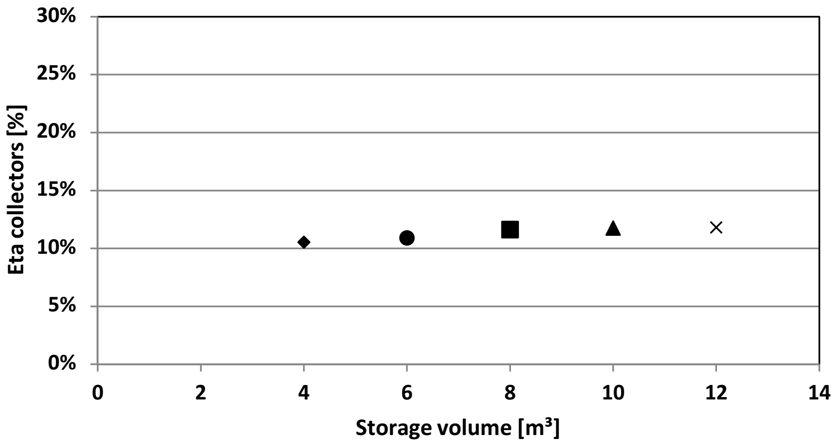
Figure 6.18: Effect of the storage volume on the system performance in Rome

Low category hotel

As can be seen for Stockholm (6.19), the maximum value of 18 % of annual solar fraction occurs between 8 and 10 m^3, while the values are around 17%, so there is a relatively small difference. The same consideration can be done also for the efficiency coefficient, which in that range is about 12%.



(a) Annual Solar Fraction value varying the storage tank volume for Stockholm - low category hotel.

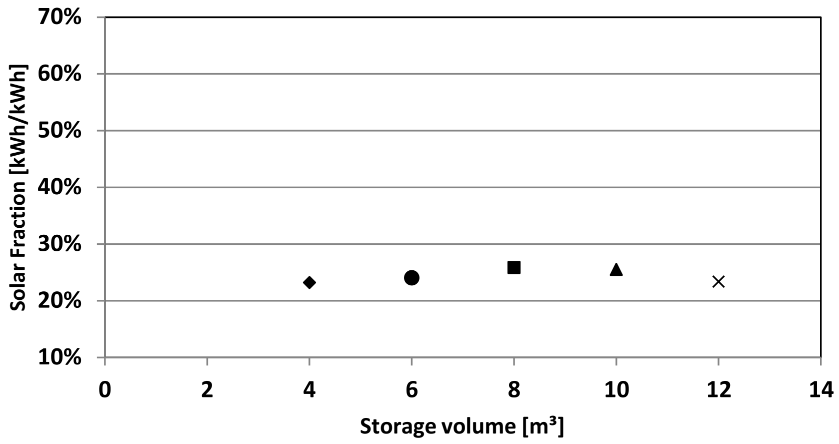


(b) Annual collector efficiency varying the storage tank volume for Stockholm - low category hotel.

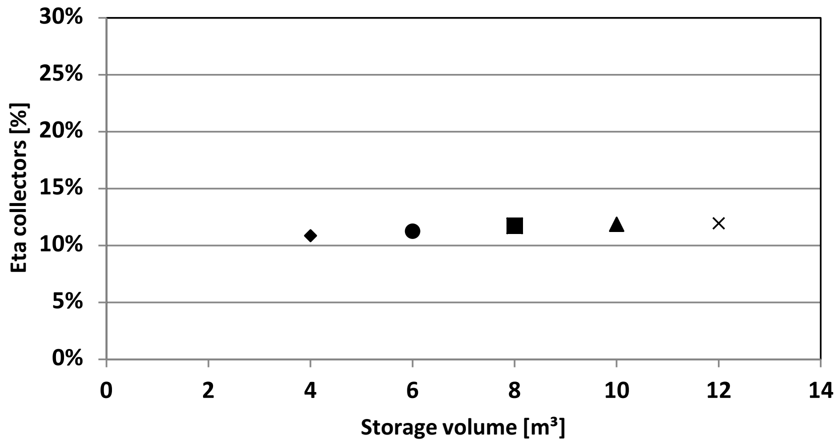
Figure 6.19: Effect of the storage volume on the system performance in Stockholm

The same consideration for Stockholm are still valid for the case of Zurich (6.20), the maximum value of annual solar fraction is 26% and occur in the range 8 – 10 m^3 of storage volume. The same consideration can be done also for the efficiency coefficient which in that range is about 12%.

In the case of Rome (Fig. 6.21), the annual solar fraction increases rapidly to the maximum value of 62% at 12 m^3, while the average is around 56%. Concerning the efficiency coefficient, it is around 14% in the range 8 – 12 m^3 of storage volume.



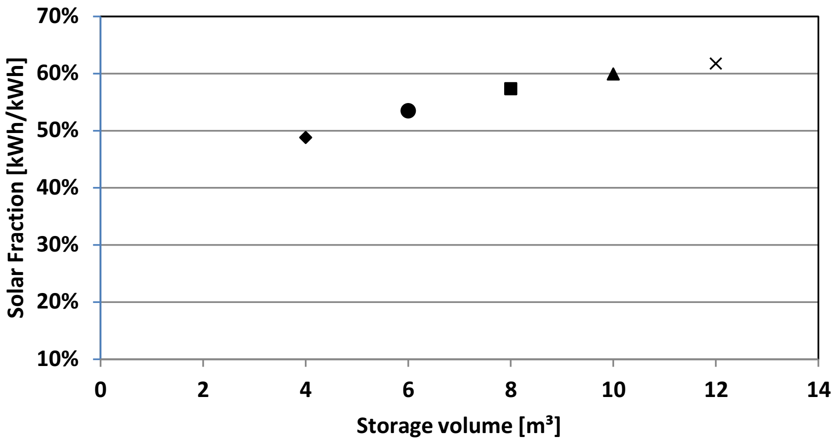
(a) Annual Solar Fraction value varying the storage tank volume for Zurich - low category hotel.



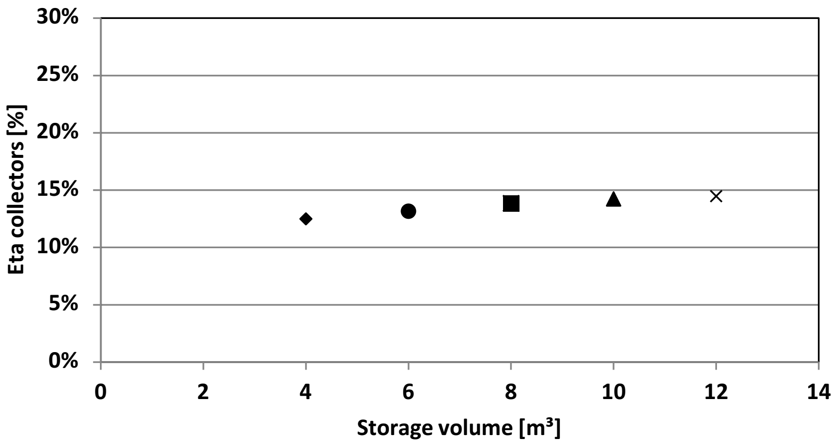
(b) Annual collector efficiency varying the storage tank volume for Zurich - low category hotel.

Figure 6.20: Effect of the storage volume on the system performance in Zurich

Considering the economical quantification of the differences in percentage of soar fraction, the maximum value of solar fraction occurs between 8 and 10 m^3, but in case the user would install a smaller volume of 6 m^3 the installation and the maintenance costs will be lower and he will spend around 168 euro (-1.7%) more every year because of the less production. For Zurich, he will spend 135 euro (-2%) more. For the case of Rome, the maximum solar fraction occurs with a storage of 12 m^3 but, since the solar irradiation is high and the temperatures as well, it is possible to install smaller volume. The further cost due to the less sthermal energy production is quantified in 100 euro for a 10 m^3 (-2%), 250 euro for 8 m^3 (-5%), 450 euro (-9%) and 650 euro (-13%) for 6



(a) Annual Solar Fraction value varying the storage tank volume for Rome - hotel.



(b) Annual collector efficiency varying the storage tank volume for Rome - low category hotel.

Figure 6.21: Effect of the storage volume on the system performance in Rome

m^3 and 4 m^3 respectively.

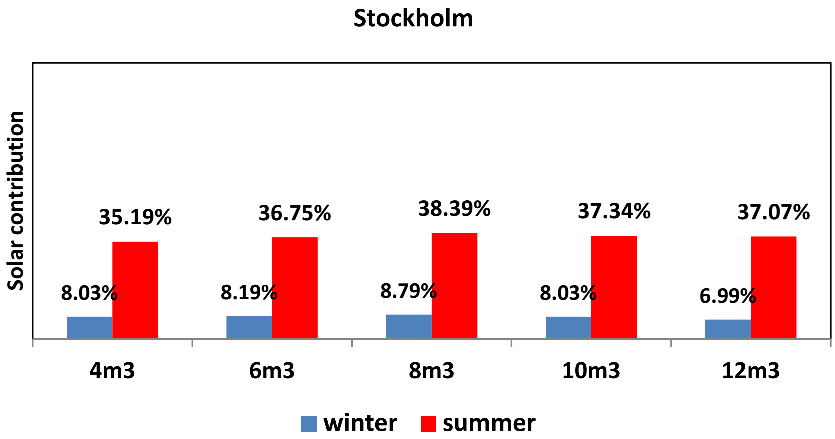
In conclusion, an 8 m^3 of storage tank volume gives in general values of annual solar fraction close to the optimum. In general, as long as the storage volume is generally around 6 and 10 m^3, the amount of solar fraction is still appreciable. Moreover, because of high costs of installation and maintenance of big storages, a volume of 6 m^3 could be taken into consideration as well.

Solar contribution for season

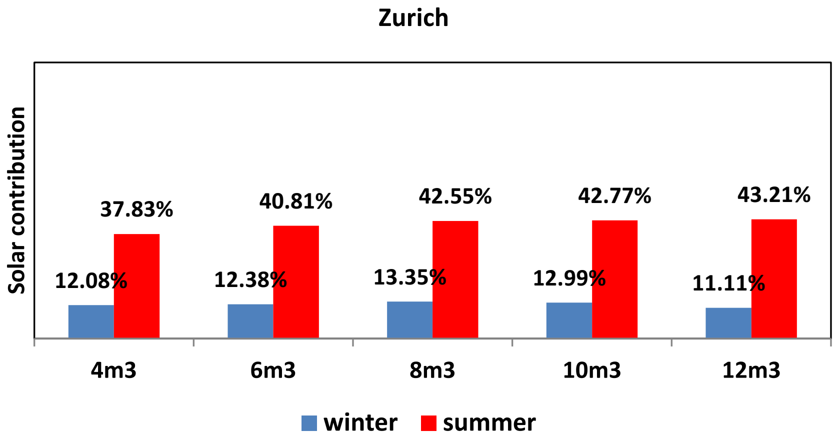
The seasonal solar contribution for the heat load for winter and summer is reported in the Figures 6.22 for the multifamily case and in the Figures 6.23 for the hotel. The solar contribution has been evaluated for the two seasons, varying the storage tank volume in the range 4–12 m^3. In summer, solar energy contributes to cover the DHW load, while in winter to cover both the DHW and space heating loads.

The contribution of the solar collectors during the winter months is not so high, especially for Stockholm and Zurich. The best performances are reached in the range 6–10 m^3 of storage, but in general the quantitative differences among the storage volume values in fulfilling the heat demand of the building are relatively small.

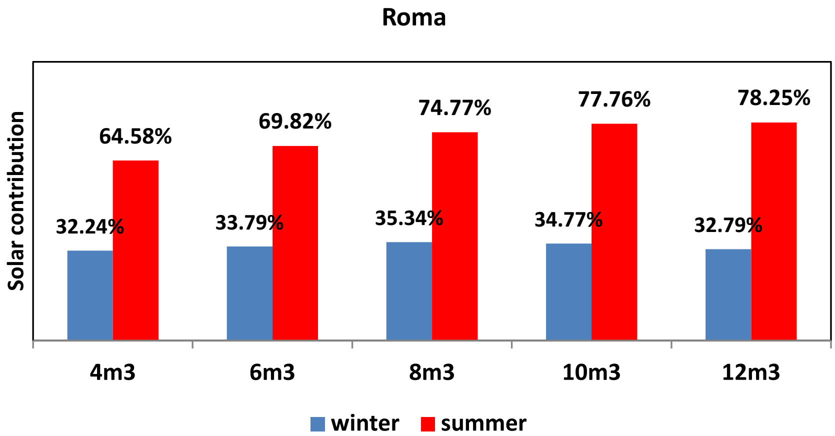
The maximum value for winter season occurs with a storage tank volume around 8 m^3 for all the three locations. For summer, this value is still valid for Stockholm, whereas in Zurich and Rome a storage tank with a volume between 10 and 12 m^3 gives a solar fraction higher than that with smaller volumes. In fact, going towards southern European locations, the available solar energy is higher and so the solar contribution.



(a) Solar contribution for the heat load in winter and in summer for the multifamily house in Stockholm.

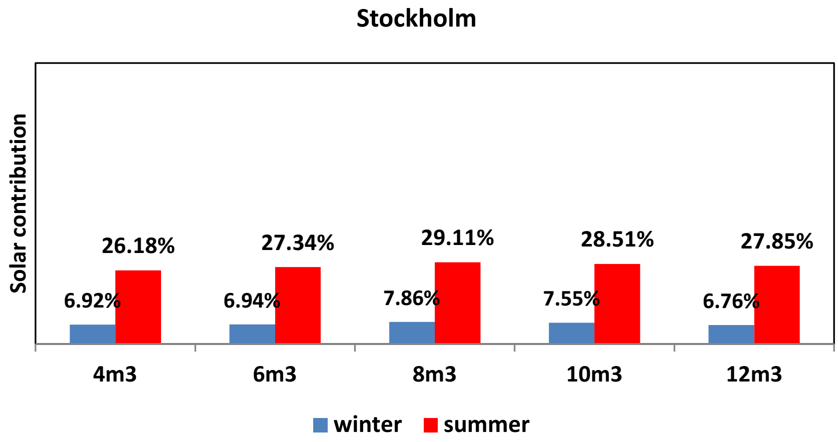


(b) Solar contribution for the heat load in winter and in summer for the multifamily house in Zurich.

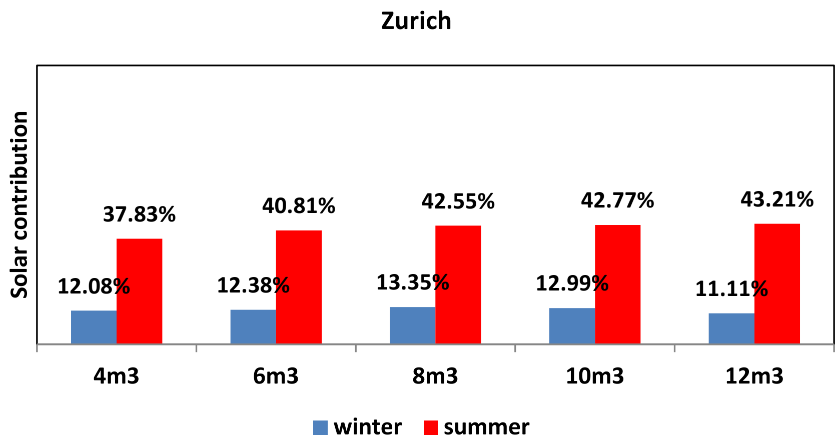


(c) Solar contribution for the heat load in winter and in summer for the multifamily house in Rome.

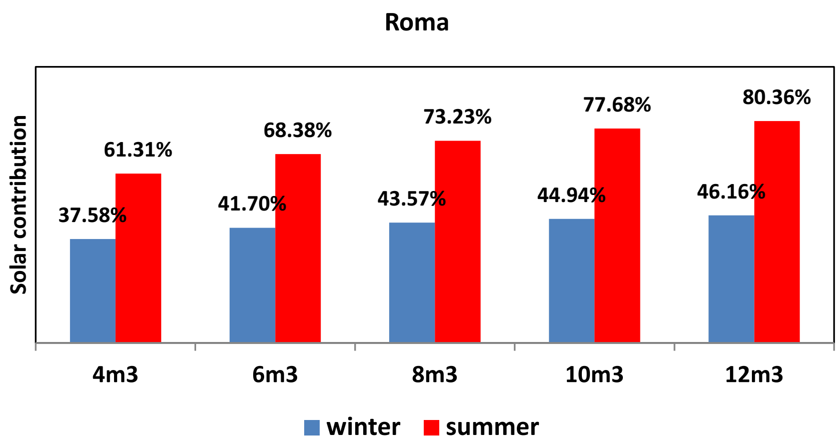
Figure 6.22: Solar contribution for the heat load in winter (DHW and space heating) and in summer (DHW only) for the multifamily house.



(a) Solar contribution for the heat load in winter and in summer for the hotel in Stockholm.



(b) Solar contribution for the heat load in winter and in summer for the hotel in Zurich.



(c) Solar contribution for the heat load in winter and in summer for the hotel in Rome.

Figure 6.23: Solar contribution for the heat load in winter (DHW and space heating) and in summer (DHW only) for the hotel.

Temperatures analysis

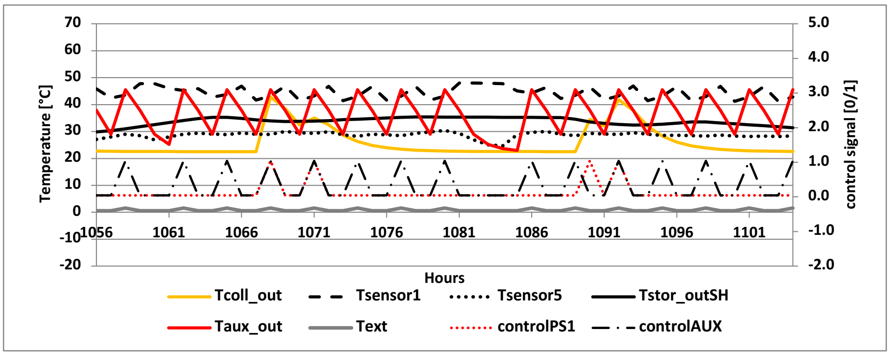
Reaching the set temperatures in the storage tank to guarantee 45°Cfor DHW and 35°Cfor SH respectively is a demanding task in winter season. When the solar energy delivered to the storage is not enough to reach the required temperature, the auxiliary heater starts to work.
In order to investigate how the energy system works during 48 hours of operation of coldest days and hottest days, it is interesting to plot and to evaluate the temperatures respectively of the fluid coming out from the collector field (T_{coll_out}), the water from the storage to the space heating system T_{stor_outSH}, the water at the top ($T_{sensor1}$) and at the bottom ($T_{sensor5}$) of the storage tank, the external environment air (T_{ext}) and the fluid coming out from the auxiliary heater (T_{aux_out}). The control signal for the solar loop (*controlPS1*) and the auxiliary heater operation (*controlAUX*) are plotted as well.

The control signal for the solar loop (*controlPS1*) and the auxiliary heater operation (*controlAUX*) are plotted as well.
The solar loop control sends a signal of switching on to the two pumps of the solar loop when two conditions are verified at the same time: (1) when the solar irradiation hitting the facade is above the value of 100 W/m^2K and (2) when the temperature drop between the water coming out the collector and the sensor at the bottom of the storage ($T_{sensor5}$) is above 7 K.
The auxiliary heater control sends a signal of switching on to the auxiliary boiler when the temperature of the sensor at the top of the storage ($T_{sensor1}$) is below the required temperature. When this temperature is reached, the gas heater stops to work.

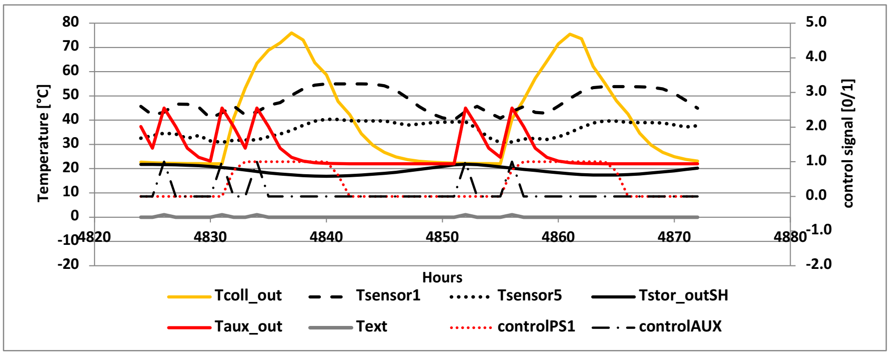
The figures 6.24(a) and 6.24(b) are referred to Stockholm for the coldest and the hottest day respectively, 6.25(a) and 6.25(b) for Zurich, 6.26(a) and 6.26(b) for Rome.

Stockholm

As can be expected, the outdoor temperature in winter (figure 6.24(a)) is under 0°Cand, even if the solar irradiation is high, the temperature coming out from the collector reach hardly 34°Cand for a short time, more probably because the heat losses are high. The auxiliary heater works often and as the temperature at the top of the storage is below 40°C. In summer (figure 6.24(b)) the outdoor temperature is between 15°Cand 30°Cand the water comes out from the collector also with a temperature up to 65°C. With these conditions, the auxiliary heater is switched off and the storage tank uses the solar contribution for a long time.



(a) Temperatures and control signal trend for the energy system operation of the multifamily house in Stockholm, coldest days.



(b) Temperatures and control signal trend for the energy system operation of the multifamily house in Stockholm, hottest days.

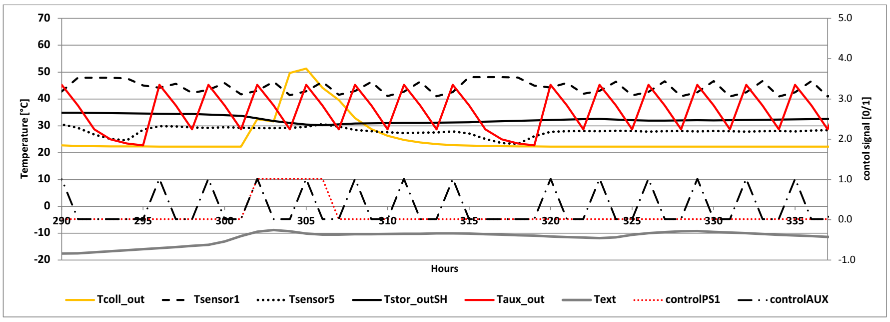
Figure 6.24: Simulation results of 48 hours of operation in the coldest day for the multifamily house located in Stockholm with flow rate 1000kg/hr and storage volume of 8 m^3.

Zurich

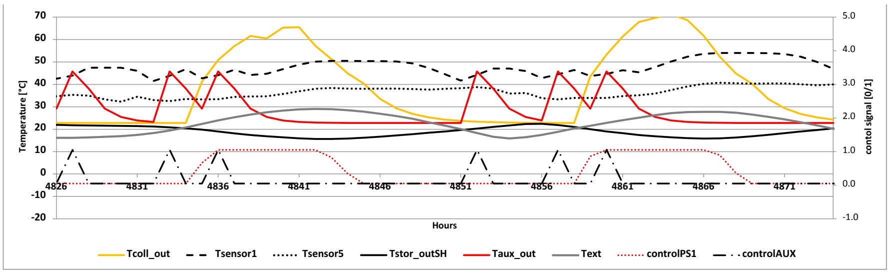
For Zurich, it can be observed the same winter trend of Stockholm, except for the fact that the solar irradiation is not available for one of the two days and therefore the pumps of the solar loop do not work. In Summer-time (Figure 6.25(b)), the auxiliary heater is still working, despite the temperatures of the collectors are quite high. This could be explained by the fact that the available irradiation is lower than in Stockholm.

Rome

As can be expected, in Rome (Figure 6.26(a) and Figure 6.26(b)) the auxiliary heater is switched on in winter when the temperature of the sensor1 is below 40℃. In summer, the set temperature in the storage is reached and maintained for a long time and so the auxiliary heater is off for both the two days, since the water delivered to the storage tank has quite high energy potential.



(a) Temperatures and control signal trend for the energy system operation of the multifamily house in Zurich, coldest days.



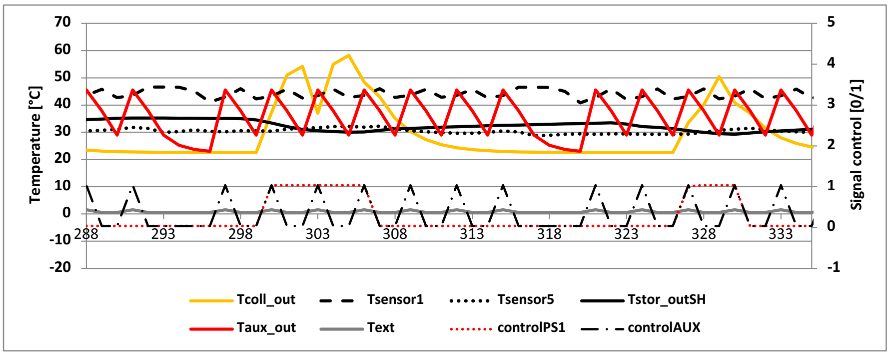
(b) Temperatures and control signal trend for the energy system operation of the multifamily house in Zurich, hottest days.

Figure 6.25: Simulation results of 48 hours of operation in the coldest day for the multifamily house located in Zurich with flow rate 1000kg/hr and storage volume 8 m^3.

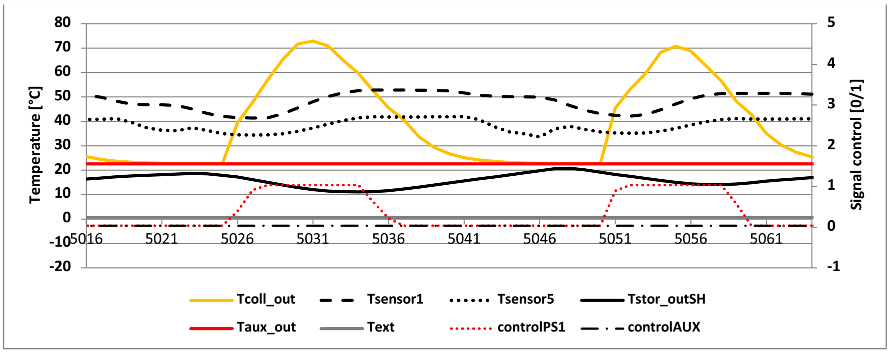
Considering this last analysis, the best performance of the combisystem combined with an UST collector (implemented in the south facade) is obtained in Rome. This might mean that this technology could have a wide success and many possibilities to be applied in Southern Europe.

A further analysis was carried out in order to reduce the operation hours of the back-up during the year. Some simulations were run in each location to understand the dependence of the gas boiler utilization on the volume of the storage (see Table 6.2).

As it can be observed, in the cases of Zurich and Stockholm a storage volume of 8 m^3 allows a minimum operation of the heater of 2139 hours and 2338 hours respectively, whereas in the case of Rome the minimum value of hours occurs with 10 m^3 with 1403 hours. In addition, for the gas heater a calculation of the amount of operation hours occurring in the coldest day has been done.



(a) Temperatures and control signal trend for the energy system operation of the multifamily house in Rome, coldest days.



(b) Temperatures and control signal trend for the energy system operation of the multifamily house in Rome, hottest days.

Figure 6.26: Simulation results of 48 hours of operation in the coldest day for the multifamily house located in Rome with flow rate 1000kg/hr and storage volume 10 m^3.

Case	Storage volume $[m^3]$	Operation hours/year $[h]$	Operation hours in the coldest day $[h]$
Stockholm	6	2765	9
	8	2338	8
	10	3544	8
Zurich	6	2496	9
	8	2139	8
	10	2156	7
Rome	6	1741	9
	8	1457	8
	10	1403	7
	12	1970	8

Table 6.2: Dependence of the storage volume on the auxiliary heater operation hours.

6.3.7 Rules of thumb for the combisystem

The parametric analyses has allowed to define some rough rules of thumb for this simple configuration of solar combisystem coupled with UST collectors.

Firstly, the flow rate running in the primary solar loop should be in the range 1000 - 2000kg/hr, in order to get water with a high energy potential to deliver to the storage tank and an effectiveness value of the external heat-exchanger around 75%. In locations placed in southern Europe like Rome, it could be possible to have higher values of flow rate till 5000 kg/hr.

Regarding the storage tank volume, it is important to remark that the sizing of the storage depends significantly on the climate and on the users.

The parametric analysis carried out for the multifamily house and the low category hotel has showed out that higher solar fraction and efficiency coefficient annual values can be generally reached considering a volume between 8 and 10 m^3, corresponding to 33.3 and 41.6 l/m^2_{coll}. In summer-time, a storage with a volume of 12 m3 (50 l/m^2_{coll}) would be better to achieve a higher solar fraction, but it is known that with the increasing of the tank volume, the heat loses increase as well. However, from an economical point of view, a storage volume of 6 m^3 (25 l/m^2_{coll}) could be enough, since the differences in percentage of solar fraction are not so high and the cost are reasonable.

A finer-tuning of this configuration would take into consideration two separated storages connected in cascade for DHW and space heating in order to improve the performance of the combisystem. Once the set temperature of 45 ℃is reached in the first storage for DHW, the valve for the second storage is switched on to supply hot water for the SH at a smaller temperature (35 ℃).

6.4 Study of the UST collector coupled with a heat pump

The concept of use of the water-water heat pump in the combisystem to cover the mismatch between solar production and building heat demand is here described.

Since in Northern and central Europe (Stockholm and Zurich) the solar contribution, given by the simple configuration of combisystem previously analysed, results not so high if compared with locations in the South (Rome), the use of a heat pump represents the proper solution in order to cover as much as possible the heat demand in winter season.

The investigation and the comparison of the energy consumption of the combisystem equipped with the heat pump with the previous simple combisystem allow to evaluate how much the choice of the heat pump can be competitive. The main target is to reduce the use of the back-up and to use as much as possible the solar energy.

The **combisystem with heat pump** configuration is modeled, as in figure 6.27, and it consists of the following components:

- UST collectors with vertical installation;
- an external heat exchanger;
- a cold storage tank;
- a heat pump;
- a back-up, connected in serial with the heat pump;
- a hot storage tank;
- controllers for the system operation (solar loop, heat pump and auxiliary heater);
- a by-pass, to deliver the water of the solar loop directly to the hot storage in case the temperature is higher than 45°C.

The Trnsys deck is presented in Figure 6.28. The deck is completed but the investigation and the parametric analysis will be provided in the future development phases.

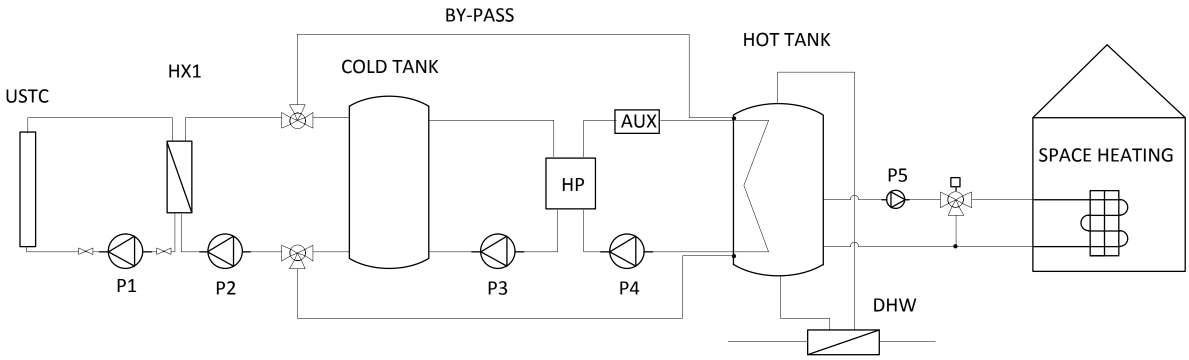


Figure 6.27: Hydraulic scheme of the combisystem provided with heat pump.

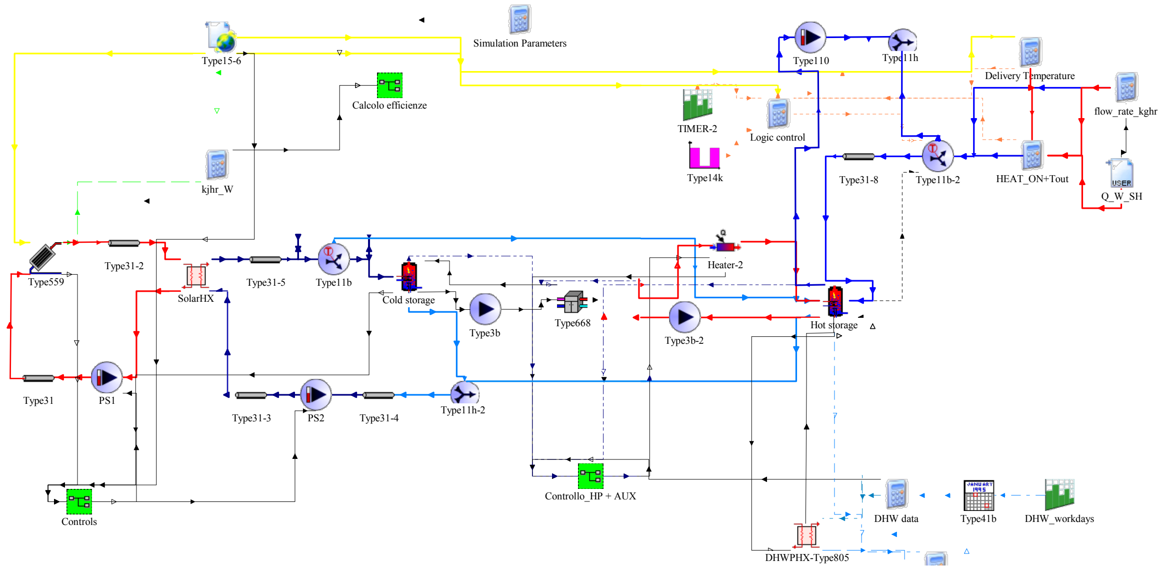


Figure 6.28: Trnsys deck of the combisystem provided with heat pump.

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7

Conclusions and further developments

7.1 Final discussion

A new unglazed solar thermal collector concept for facade integration in building energy retrofit actions was developed.

The main contribution of this work was to show the potentiality and the development opportunities as well as the problems of merging two technologies, roll-bond technology and metal cladding system, into one component in order to answer both the engineering and architectural aspects related to the integration of solar thermal in the building envelope. The above mentioned product has been conceived to be low-cost, therefore it should not cost much more than a classic metal cladding in order to be competitive with other products for the building energy retrofit.

The idea of development of an unglazed solar thermal collector to integrate in facade as metal cladding system was not an impracticable concept. There was an important preliminary phase having the purpose to verify the feasibility of the proposal and the potential applicability from the technological standpoint.

The first step was to create networking among research – dealing with building and collector' materials – and industrial partners – both facade manufacturer and roll-bond evaporator producer – to build cooperation relationships in order to plan the design and development phases of a prototype. The technological effort to create synergy among the partners was part of the present research activity path, although not mentioned in this thesis.

In order to deepen the subject of the integrating solar thermal system into facade and analyzing the architectural aspect and issues, in 2010 a short period of the research activity was spent over the Laboratoire d'Energie solaire et de physique du Batiment (LESO-PB) at EPFL - Ecole Polytechnique Federale de Lausanne in Switzerland, in the research team of C. Roecker. Part of the team activities concerned the quality of the architectural integration of ST system in buildings.

Unfortunately, some changes in the research activity path have been done in the following few months mainly due to lack of funding to invest in the realization of the prototype and technology.

The research work has focused mainly on investigating the potentialities of the UST collector through an architectural pre-design, to develop a possible facade concept, and dynamic simulations, to analyse the energy performances.

The context analysis provided first a breakdown of building stock, whose energy consumptions has been given. Finally, the state of the art provided an overview on the solar thermal technologies available on the market for facade applications. The analysis of the state of the art revealed the limits and barriers of the existing ST products related to their envelope integrability to answer both thermal energy production and architectural issues. In that respect, the roll-bond absorber technology was investigated as a promising technical solution. From another point of view, metal cladding facade coverage was presented as a technique to answer the aesthetic/architectural issue.

These fundamentals stated, it was possible to show what there was still to do in the building field to make the spreading of ST technologies easier and to go deeply in details in the design of a new solar technology integrated in the facade.

In the concept design and development phases of a new solar thermal technology for facade, there were and still are more or less complex hydraulic, structural and architectural issues to deal with.

The real core of the thesis was the methodological approach developed to address the design of the unglazed solar thermal/facade cladding system and to study the facade concept following three main steps:

1. description of technical and architectural integration problems to select the proper suitable cladding system between plank and cassette;

2. heat transfer and fluid dynamic assessment of the physical interaction of the new facade on the existing one through a finite element method tool. The production of heat in facade could be positive in winter because it would help to reduce the heat losses from the building, whereas in summer it could overheat the indoor spaces;

3. modeling of the Building Integrated Solar Thermal (BIST), as part of the building energy system, through the TRNSYS dynamic simulation tool.

The modeling of the element was pursued going from the simplest to the most complex aspect, and according to the integration degree in the building: (1) study of the single collector, (2) study of the collectors implemented in facade and (3) study of the collectors' field connected to the building energy system.

One of the important part of the activity was the modeling of the UST collector as a component of the energy system of two building typologies (different internal loads) – a low category hotel and a multifamily house – under three different weather conditions (different external loads) – Stockholm, Zurich and Rome. The model of the energy system was built with the support of Trnsys and the base problem that was faced was to define and couple the proper typology of the whole building energy system with the UST collector field.

Since it is a technology working at low temperature and conceived to be implemented in facade, high surfaces were necessary and so the parameters and controllers of the energy system had to be carefully set. An important achievement of the thesis was to provide general rules to size this kind of UST collector on the facade.

A first parametric analyses carried out on a simple Trnsys deck, consisting in the type 559 modeling the UST collector, allowed to understand the influence of some design parameters and therefore to individuate the flow rate-to-collector area, which represented the best compromise between collector efficiency and outlet temperatures. The simulations were run for various solar collecting surface and mass flow rate, in order to evaluate how the efficiency and the outlet temperature changed.

The results showed out firstly that the collector thermal energy production and the efficiency were strongly correlated to the mass flow rate, whereas the collector area had a great effect on the temperatures.

Since the objective was to have a good balance between (1) a useful energy quantity collected by the solar collectors and (2) outlet temperatures as high as possible, values of flow rates-to-collector area less than 10 kg/(hr.m^2) allowed having higher temperatures coming out from the collector (high energy quality) as well as higher inlet/outlet temperature differences (high energy quantity).

Hence, this meant to consider (1) large collector areas and (2) low flow rates for the sizing of the energy system when connected to the UST collector. Since the southern facade of the two reference buildings - 300 m^2 for the small hotel and 240 m^2 for the multifamily house respectively - had a large surface available, one of the possible configuration of the solar collector field could be to cover the overall surface of the facade with UST collector and to vary the flow rate in the range from 1000 to 10000kg/hr.

The second part of the parametric approach aimed at investigating the potentialities of the UST collector when integrated in a building combisystem, for combined space heating and domestic hot water supply, and when all the available facade surface is used. In this case, the parameters and controllers of the energy system had to be carefully set.

The objectives were (1) to evaluate the energy performance and (2) to provide general rules of thumb to size this kind of UST collector on the facade, in order to decrease the back-up system (e.g. gas heater) and increase the solar collectors' utilization as well as the solar fraction.

The results showed firstly that the flow rate running in the primary solar loop should be selected in the range 1000 - 2000kg/hr, in order to get water with a high energy potential to deliver to the storage tank and an effectiveness value of the external heat-exchanger around 75%. In locations placed in southern Europe like Rome, it could be possible to have higher values of flow rate up to 5000 kg/hr.

Regarding the storage tank volume, the parametric analysis carried out for the multifamily house showed that higher solar fraction and efficiency coefficient annual values can be generally reached considering a tank volume-to-collector area ratio between 33.3 and 41.6 l/m^2_{coll}. During summer-time, a storage with a higher volume would be better to achieve a higher solar fraction. However, from an economical point of view, a storage volume of 25 l/m^2_{coll} could be enough, since the differences in percentage of solar fraction are not so high and the costs are reasonable.

The concept of couple the UST cladding with a water-water heat pump in the combisystem, to cover the mismatch between solar production and building heat demand, was considered and a layout of the system was designed. The sizing of a combisystem, equipped with a heat pump, is a complex procedure because a lot of several variables must be taken into account in the parametric analysis.

Further research work is needed to tune the combisystem layout and define the optimal control strategies.

7.2 Further developments

The aims of the research activity were originally to conceive, to design and finally to build a prototype of the solar active building element. Along such a path, there are always a lot of interconnected aspects and variables to be taken into consideration and to be studied, since all of them play an important role in defining the best solution.

The present work focused on a pre-design and on a parametric analysis of the element to (1) address the design and the prototyping and to (2) suggest rough rule of thumbs for the sizing of a combisystem coupled with the unglazed solar thermal collector.

There are other aspects left over that should be taken into consideration:

Design optimization of the structural and hydraulic schemes in function of the constructive technology system.

Parametrization it is interesting to parametrize the solar active facade depending on weather conditions (North, Center and South of Europe) and on the building (thermal load to satisfy, thickness and properties of the existing constructive packages).

UST facade modeling in Trnsys the Trnsys model of the UST should be improved in some details. A measurement campaign on the prototype should be done in order to validate the model.

Combisystem optimization A finer-tuning of this configuration would take into consideration two separated storages for DHW and space heating, in order to improve the performance of the combisystem, and new strategies of control.

Combisystem with heat pump the Trnsys simulation model of the system equipped with a heat pump is interesting since the unglazed collector can be used to pre-heat the water

Prototype prototyping, in cooperation with roll-bond and facade manufacturers, since it represents a tangible means of obtaining a qualitative and complete understanding of the opportunities and problems of this technology.

Laboratory test testing phase of the prototype in a guarded hot box, placed in EURAC laboratory. INTENT test facility is a calorimeter that allows to emulate indoor and outdoor building environment. The calorimeter is equipped with an artificial sun in the cold chamber working with a variable power, and with a hydraulic circuit, whit which it is possible to emulate the loads of the building users, and to assess the performance of the solar thermal collector as well as to evaluate the thermal properties of active envelopes in dynamic conditions.

7.3 Conclusion

The target of this work was to propose and study an innovative and promising technology of active solar facade and to define a general solution. The purpose is possibly to develop this component as energy retrofit package and to contribute to the building stock transformation.