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Developing a tool to assess the business concept of solar thermal façades

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Working hard for something we don't care about is called stress; working hard for something we love is called passion.

Simon Sinek

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Abstract

The energy production from solar radiation hitting building façades has a huge potential to be usefully exploited due to their large surface area, especially for buildings having many floors and scarce availability of roof surface area. Nevertheless, risks and uncertainties of solar technologies integration scare designers and façade manufacturers. An analysis of aspects to be considered during the design of solar thermal façades, the potential failures and maintenance needs, but also the effort necessary to implement the new technology within the façade production chain of a façade manufacturing factory is carried out to assess how these aspects can be included in a business concept.

Building envelope systems may have a great impact in terms of energy performance and economics for both new constructions and building refurbishment. However, there is still a lack of tools supporting an easy life cycle costs analysis and the assessment of economic risks linked to the integration of energy delivering components like photovoltaic panels and solar thermal collectors, mainly due to the uncertainties about the variability of costs, subsidies and responsibilities in case of failure. This makes business models for exploiting the potential of active façades an extremely current research topic.

When complexity is introduced into the building envelope, designers and façade manufacturers know that the investment cost will be higher than standard solutions. Though, what they do fear is the uncertainty of operation and maintenance expenses over time. The economic feasibility of complex façade concepts should not just be focused on the initial cost. Indeed, the effect of design choices and uncertainties should be quantified in economic terms over time.

A user-friendly tool mainly addressed to technical managers, engineers and architects was developed to show this effect and to ease the communication of performance indicators of complex façade systems during the early design stage. The excel spreadsheet, called FAST-IN tool (Feasibility Assessment of Solar Technologies Integration), focuses on active solar façades and is aimed to support the user to set priorities, while evaluating several envelope-energy system configurations through a technical and economic assessment of selected interventions. The strength of the instrument is linked to the multidisciplinary-based approach giving the user the chance to set inputs relative to technologies, maintenance recurrence and related costs, energy efficiency and financial mechanisms to bear the initial cost and eventually pay back the extra-cost of investment in comparison with other solutions. Technologies refer to solar active façade concepts, passive façade solutions and various energy systems; therefore, the instrument is flexible to a certain extent.

The proposed tool was extensively experimented in the analysis of a solar thermal façade developed within an industrial project. This project aimed to demonstrate the technical feasibility of a solar energy generation-storage and distribution concept integrated in a unitized façade system, while the tool's objective is providing a life cycle cost perspective considering the effect of technical choices and potential business concepts. This façade concept has been taken as a complex case study to be assessed, in such a way that is facilitated the implementation of other façade concepts and energy systems.

Contents

Abbreviations and Nomenclature

a_1: linear heat loss coefficient according to EN 12975-2 in W/(m²K)

a_2: quadratic heat loss coefficient according to EN 12975-2 in W/(m²K²)

ACH: air change per hour

ASTF: Active Solar Thermal Façade

BIPV: Building Integrated Photovoltaic

BIST: Building Integrated Solar Thermal

DF: Distributive Façade

DHW: Domestic Hot Water

DSF: Double Skin Façade

G hemispherical irradiance in W/m²

h_c: convective heat transfer coefficient in W/(m²K)

h_r: radiative heat transfer coefficient in W/(m²K)

HVAC: Heatin, Ventilation, Air Conditioning

IGU: Insulation Glazing Unit

PF: Passive Façade

PV: Photovoltaic

PVF: Photovoltaic Façade

RES: Renewable Energy Sources

SC: Space Cooling

SH: Space Heating

STC: Solar Thermal Collector

STF: Solar Thermal Façade

STS: Solar Thermal System

T_a: ambient air temperature in °C

T_{fl}: mean fluid temperature in K

T_{in}: internal air temperature in °C

Α: solar absorption

β: collector tilt angle in degree

ε: thermal emissivity

η: collector efficiency

η_0: conversion factor according to EN 12975-2

τ: solar transmittance

Chapter 1

1 Supporting the business concept behind complex façades

Why is it difficult spreading new building integrated façade concepts? The need of performance data, robust and affordable technologies and dedicated financial supports are necessary to encourage the development of new façade technologies. According to the European Solar Thermal Technology Platform (ESTTP) experts [1]*, new business models must be developed to overcome the barrier for financing upfront costs. Concepts for outsourcing technical and economic risks, and offering further energy related services, should be advanced as well. Innovative marketing strategies should be elaborated based on market research to stimulate the refurbishment of the existing building stock and heating systems with modern solar thermal heating systems. Before developing a business model for solar façades, new business concepts for enhancing the market introduction of thermal technologies are needed. The façade market and the solar-based technology market could create demand one each other.*

Keywords: business concept; complex façades, active envelope

1.1 Recent developments in the field of façades

The evolution of construction materials, façade systems and components has led the façade sector towards the desire to associate the building envelope to the human skin, making it more responsive and adaptive. We could summarize the concept of adaptiveness through three sentences:

Insulate when needed

Produce energy when possible

Shade and ventilate according to comfort needs

To fulfil these functions, active components are necessary. At least for the second one. Since ancient times, walls have been thought to protect people living within them, which is a function. As reported by Tilmann Klein [2], "functions are the requirements that a product has to fulfil. Functionality is a property that can be used to fulfil a product function. A façade function would be supplying fresh air to the interior of the building. An operable window is a functionality that could be used for this purpose. However, a mechanical ventilation unit could fulfill the same objective, while operable windows could be used for window cleaning."

During the last two centuries, big strides have been made in the façade sector. Figure 1 shows the evolution of the envelope technology from the industrial revolution until today. The modern façade history starts with the English gardener Joseph Paxton, known for designing the Crystal Palace envelope made with iron and glass. The invention of new materials like the reinforced concrete and insulations, but also new processing techniques like the extrusion of profiles, have launched new façade systems; sometimes these are just components, in other cases actual façade systems. The research on active façades has begun during the 80's with first applications in the 90's, while the last frontier in the field are adaptive façades.

Active façades are those interacting with the building by means of integrated active components like photovoltaic modules, solar thermal collectors, mechanical ventilation units, sensors regulating the opening of windows, and many others. In order to be competitive, an active façade system should not cover a function which is already fulfilled by another product in the building, but it should substitute that product otherwise it is not worth the trouble. Hence, if solar thermal collectors are already installed on the roof, they should not be integrated into façade, and reversing the situation, if a distribution system is integrated into façade no fan-coils or other emission elements should be installed inside the building.

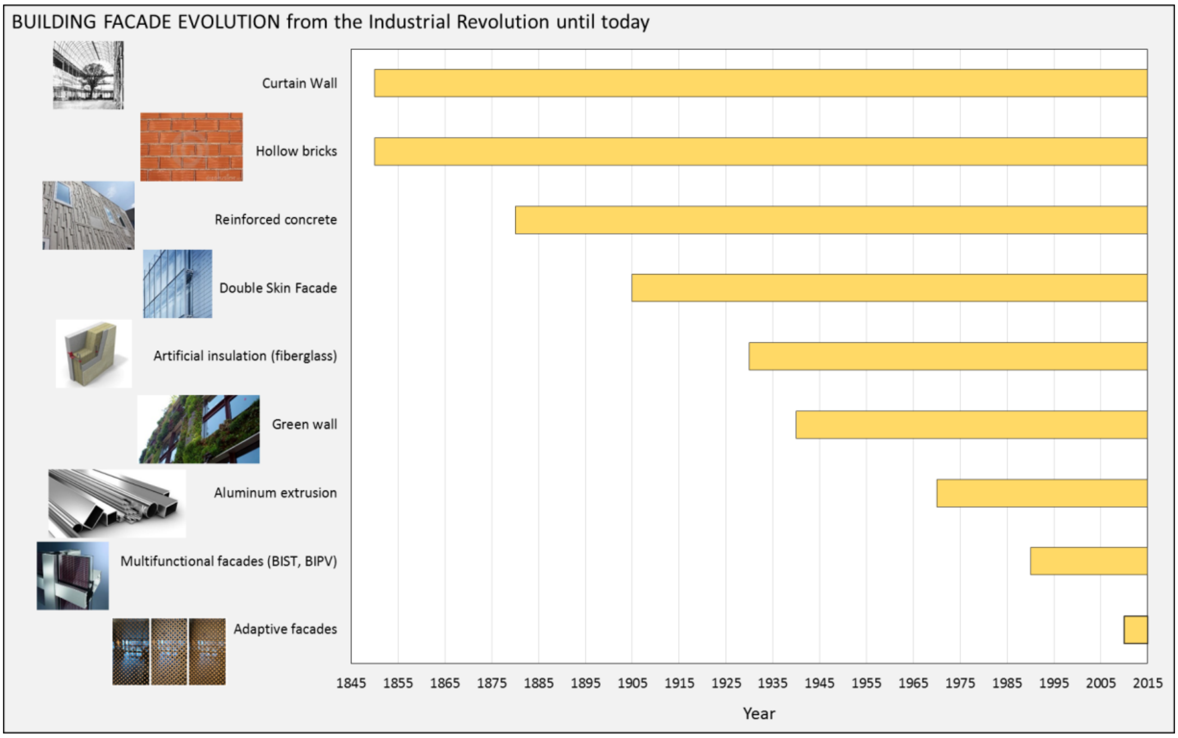


Figure 1 - Evolution of façade systems during the last 200 years

The low thermal insulation in buildings has led to considerable energy consumptions for space heating and domestic ho/warm water production. On the other hand, air conditioning is acquiring dominancy due to the massive use of fully glazed façades and to the higher number of appliances increasing the internal loads. The façade surface area exposed to solar radiation is significant. As highlighted by Cruz Lopez, "the challenge is to take the solar energy that strikes the façade and transform it into a specific type of energy helping covering building needs, e.g. activating heating and cooling processes". [3]

More than 40% of the savings expected in heating and cooling energy demand under a low-carbon scenario can be directly attributable to improvements in the building envelope. Lower heating and cooling requirements will also allow downsizing of the equipment needed to reach a desired indoor temperature [4].

European Commission has been financing several projects dealing with the development of multifunctional, active, responsive façade concepts. Especially for the renovation of the building stock, which is another challenge of this era. Prefabrication is becoming increasingly diffused to reduce on-site operations and to have the minimum disruption on occupants.

A list of R&D projects related to prefabricated and active façades is here reported:

- *TES EnergyFaçade (2006-2011): multifunctional timber-based elements system for improving energy efficiency of the building envelope [5]*
- *IEA Annex50 (2006-2011): prefabricated Systems for Low Energy Renovation of Residential Buildings [6]*

- *E2Rebuild (2011-2014): transforming the retrofitting construction sector [7]*
- *FP7 Cost-Effective (2008-2012): converts façades into multifunctional, energy gaining components (commercial high-rise buildings) [8]*
- *FP7 EASEE (2011-2014): improvement of the energy performance of existing residential building stock through a new holistic approach to envelope retrofitting based on a combination of prefabricated components, novel insulation approaches for the cavity wall and innovative insulating solutions for the interiors [9]*
- *FP7 RETROKIT (2007-2013): development and demonstration of multifunctional, modular, low cost and easy to install prefabricated modules in order to significantly increase the EU retrofitting rate and contribute to EU energy reduction commitments [10]*
- *FP7 INSPIRE (2012-2016): tackle the problem of high-energy consumption by producing systemic renovation packages that can be applied to residential and tertiary buildings [11]*
- *FP7 MEEFS (2012-ongoing project): development, evaluation, and demonstration of an innovative multifunctional façade system geared towards the residential building sector [12]*

The prefabrication rate of façades can be more or less motivated, depending on the building typology and the energy needs. In case of commercial buildings, the consolidated constructive technologies (cell curtain walls, transom and mullion, double skin façades) are a good starting point to consider the integration of new components. Figures below show both passive and active prefabricated façade systems.

Figure 2 - Prefabricated passive façade modules (source: I-Tech-Bois [13])

Figure 3 - Prefabricated multifunctional façade with integrated solar thermal collectors (source: Heliopan [14])

In addition, single envelope components can be multifunctional like chromogenic glazing systems changing their properties as function of external forcing (light, temperature or voltage difference) to fulfill to thermal and comfort needs.

Among prefabricated multifunctional façades, there are those integrating solar power technologies like photovoltaic cells or modules and solar thermal absorbers or collectors. These are called *solar façades*, and can be distinguished in Building Integrated Solar Thermal (BIST) façades and Building Integrated PhotoVoltaic (BIPV) façades. The type of building integration influences the building physics of the envelope, especially when an active system replaces conventional building components.

Solar thermal collectors (STCs) and photovoltaic (PV) panels are two different products but compete on the market as energy delivering technologies. One of the differences regards the way the energy is stored when users do not use it directly: with PV systems, the connection with the electric grid is easy but the network overload risk is possible. For this reason, batteries are becoming more and more object of discussion among experts, but still is an expensive option. This is not an issue if the building use allows a good load match between production and need of electricity. PV based solutions are also favored for all-electric installation scenarios; indeed, some nations are reducing their dependence on natural gas delivering countries to rely on electricity use only. On the other hand, STCs require on-site systems to store the produced energy through centralized or decentralized tanks. Eventually, exploitation of solar energy to cover part of the cooling demand is an option under investigation by several research institutions and industries, but more complex than the connection of a PV system to a heat pump to feed air-condition units.

Although excellent products have been developed and demonstrated as ready for the market, active façades still show uncertainties due to failure risks, performance drops over time and necessary maintenance. To assume the responsibility on these uncertainties, companies apply high costs and marketing these solutions becomes unsustainable. An instrument helping mainly designers and façade and energy consultants to find a common language and to assess the lifetime costs of buildings with active façade systems is necessary.

Deciding whether to install solar façades is first of all a design choice, which will be considered more and more to achieve strict energy targets for both new and existing buildings in the near future. Motivating is the case of high-rise buildings, where the roof area is small in proportion to the usable floor area and the façade surface area. Indeed, roofs would not be appropriate to provide a sufficient active area to fulfill minimum requirements in terms of energy demand covered by renewable energy sources (RES) like 50% of domestic hot water. Solar façades will be a necessary measure in a few years. That is the reason why designers should deal with solutions for the entire building envelope. One of the obstacles for the spread of BIST and BIPV façades is the lack of knowledge to predict their performance. Energy simulation tools do not implement ready-to-use façade models. It is necessary to model the interaction among solar radiation, solar power technologies, envelope and thermal zones. This aspect, together with technology risks and a not clear responsibility structure, makes these façade systems not affordable.

1.2 Solar façades as energy delivering systems

The story of solar façades grew out of the neutralization effect of energy fluxes and it continued towards the possibility to cover part of heating, domestic hot water (DHW) and, lately, cooling energy needs. Technical developments have been pursuing for years to optimize solar façade systems.

Back to the early 20th century, we can find one of the first studies and applications of solar thermal façades (STFs). Indeed, the modern history of active glass and the essential concept of the double skin façade (DSF) was first explored and tested by Le Corbusier. He came up with a new idea called *Mur neutralisant* (neutralizing wall) consisting in including pipes between large layers of glass to favor the flow of heated or cooled fluid. He wanted to neutralize the effect of the external climate. Le Corbusier had experienced a similar concept for the windows in his Villa Schwob in Switzerland by 1916. Large windows were designed with two layers, including heating pipes in-between, to prevent down draughts.

The same system was proposed to a Russian client. Within the *Centrosoyuz project* in Moscow, another great intuition by Le Corbusier was the double wall concept applied to opaque walls. An air cavity enclosed between two walls of pink tufa stone from the Caucasus would have been a very adequate thermal solution for opaque walls in Moscow, even without hot air circuits inside. Finally, the Russian client dismissed the *Mur neutralisant* system because of the lack of technical justification, but he kept the double glazed wall, which can be considered a passive solar façade.

Figure 4 – Centrosoyuz after the opening (left) and today (middle and right) [15]

Summing up, the lack of technical data was decisive for the scheme proposed by the designer. This is still a problem creating an obstacle to the spread of solar façade concepts at the present time.

Façade systems integrating tubes to generate heat from the sun have been developed recently. Figure 5 shows an example of curtain wall where the fluid collector has been integrated in the façade aluminum mullion. Parabolic-shaped elements maximize the solar energy reaching the absorber within the vacuum tubes, which operate also as shading elements.

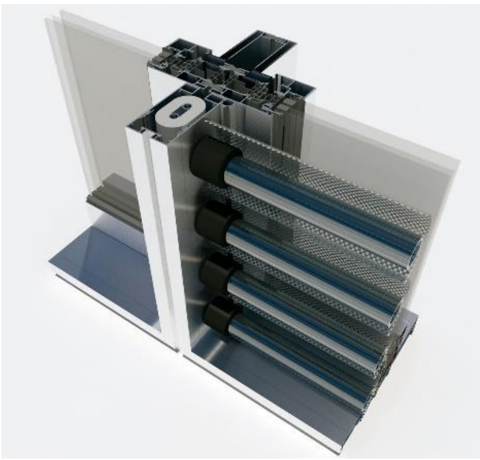


Figure 5 – Curtain wall system integrating vacuum tube collectors, 2013

Currently, space heating and cooling, together with DHW production, are estimated to account for nearly 60% of global energy consumption in buildings. They therefore represent the largest opportunity to reduce buildings' energy consumption, improve energy security and reduce CO2 emissions, particularly due to the fact that space and water heating provision in some countries is dominated by fossil fuels [4]. The EUs average renovation rate should be tripled from the current 1% to 3% per year before 2020 and it should be maintained over time [16].

The intervention on building envelope has a great potential for reducing energy consumptions and improving energy efficiency. Façade is just a part of the building envelope, but most of the time is the main energy dispersing surface area in a building. This is the reason why renovating it, means obtain a big benefit. Strategies to decide which buildings have the priority to be retrofitted can help to speed up the effectiveness of renovation processes. The other question is how to retrofit the façade of these buildings. In order to meet the strict energy targets, both in case of renovation and new construction, buildings have first to lose as less energy as possible. Eventually they have to produce energy to cover partially (nearly Zero Energy Building) or totally (Net Zero Energy Building) the remaining part of energy. One of the approaches to produce energy is making the façade a solar energy collector. This energy can be used to produce thermal energy or electricity depending on the installed technologies.

Schüco has developed a solution for retrofitting building from the outside with a minimal invasiveness. The so-called *Modernization Façade ERC50* system allows to integrate a decentralized ventilation system, photovoltaic panels and new roller shutters [17]. On the other side, standardisation limits architectural flexibility.

Installing solar thermal technologies on façade does not reduce very much the productivity; despite a little decrease in production during winter, when heat is needed, overheating risk during summer is reduced. The production of thermal energy during the summer season, when heat is less needed, is a minor concern, but still remains an issue. The real issue of solar technologies on façade regards shading elements, a phenomenon that is more likely to interest façade applications than roof ones.

Most of the solar thermal collectors are designed as pure technical components for implementation on rooftops where the visual impact is minor and the energy efficiency maximized thanks to the tilted mounting. Plants for DHW are then usually installed on the roof and are undersized to avoid over production and the consequent overheating risk in summer time: for this reason they cover 30 to 60% of the annual DHW needs. Overheating represents the main risk for glazed flat plate and evacuated tube systems. The absorber temperature of a 45° tilted glazed collector can exceed 200° C in summer in case of over production, with consequent collector stagnation; this temperature can rise up to 300° C in an evacuated tube [18]. Such temperatures can damage plastic and silicone parts. Façade use increases the available exposed surfaces, and vertical mounting reduces the overheating risk in summer, allowing the sizing of the plant according to real heat needs.

As reported by Stadler [19], factors between 1 and 2 should be applied to get the same solar fraction of collectors installed on roof, but the reduced heat transfer outwards through the wall was not taken into account. For systems producing energy for both space heating and DHW, the bigger the solar fraction the lower the difference between façade and roof in terms of needed collectors area. The graph reported in Figure 6 shows the multiplier factor to be applied to a solar thermal collector surface area installed with a 45° tilt depending on energy needs to be covered (only DHW or DHW+Space Heating) and the solar fraction to be achieved (reported on the x-axis). It can be observed that installing solar thermal collectors on façade to cover only domestic hot water is not a cost-benefit action, while covering both DHW and space heating needs reduces the difference between needed active surface on façade and roof, especially if high solar fractions are desired.

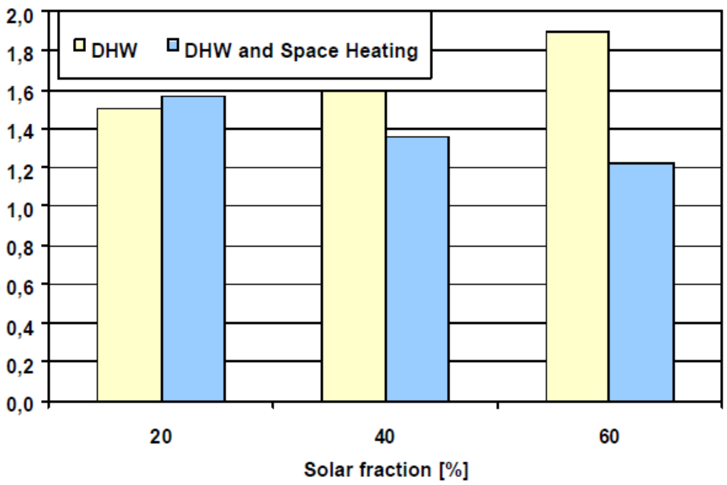


Figure 6 - Collector area on façade against collector area on roof (tilt 45°) to achieve different solar fraction for different energy needs [19]

One of the main obstacles for solar thermal façades is the difficulty to aesthetically integrate the available collectors on the market, mainly targeted to roof implementation and developed just as technical elements for energy production. Another barrier is linked to the color and the appearance: absorbers usually are black, and piping or absorber irregularities are visible through the glazing. Munari Probst [18] investigated on the façade integration issues and she came up with a new product integrating selective filters reflecting only a small part of the solar spectrum in the visible range while letting the rest of the radiation heating the absorber. These filters were successfully produced and have achieved the desired masking effect with minor impact on the collector efficiency (less than 10%), thanks to a combined diffusing glass treatment. Using a glazing system as both collector external glass and passive façade cladding can help accelerating the market penetration of active solar façade solutions. The effect is illustrated in Figure 7.

Figure 7 – Solar thermal façade elements (dark blue and red) and dummy elements (light blue and white) [18]

The masking effect takes place only when direct light hits the glass otherwise the absorber remains visible. To obtain the desired masking effect in all conditions, the colored coating deposited on the inner side of the glazing is combined with a diffusing surface treatment on the outer side. The general very low quality of the existing collectors' integration limits their use to a small portion of the building stock.

O'Hegarty et al. [20] indicated a rule of thumb concerning colored solar thermal collectors: if a darker color is desirable, one should color the absorber, while if a lighter color is desirable one should color the cover if possible, hence the glass of flat plate glazed collectors. They also showed that the daily efficiency is reduced by approximately 4% for lighter colors (yellow) and 9% for darker colors (blue) by applying thin film technology to include color for flat plat collector covers.

A problem of solar thermal technologies is that solar thermal energy is mostly available when needed less, namely during summer. Collecting the extra energy produced during summer in order to be used in a later stage or headed to other buildings needing warm water could be essential. Energy storage strategies integrated within the building envelope and the internal building components have been matter of research during last years. Phase change materials are used in building construction in order to substitute the thermal mass of a building in case of lightweight constructions. Thermal mass activation in a building may be decisive for the reduction of cooling loads and the reduction of temperature increases.

Solar façades are matter of interest of either designers, façade companies and research institutions. A new Task, within the IEA program, started in March 2016 and it is going to deal with *Building Integrated Solar Envelope Systems for HVAC and lighting* for the next 4 years. Within Task 56, existing technologies suited for solar envelopes will be investigated and a focus on modeling and simulation is foreseen, both at façade scale and at building scale. The task is coordinated by the Institute for Renewable Energy of EURAC Research [21].

1.3 The need of business approaches for innovative façade systems

Why solar façades are not so popular? What is needed to become a more accepted product/solution by designers and society?

A *business approach* for a product could be interpreted as *How to guarantee that the social community unanimously accepts that product*. Over time, business models have been created for cellphones, cars, furniture, and search engines. Hence, products we are used to using every day. When it comes to façade systems, the term might sound a bit strange since these are not common products, and they affect only a specific clientele.

Business models are necessary to bring findings to market and to satisfy unanswered customer needs. This happens when industrial innovation occurs. But what can be included in innovation? Various definitions of innovation have been developed over the years. As cited by Stef van der Meulen and Ivan Villagomez Garcia [22], the Austro-Hungarian economist Schumpeter was the first to recognize the importance of understanding innovation. Schumpeter (1934) stated that there are five cases of innovation:

1. *Introduction of a new good*
2. *Introduction of a new method of production*
3. *Opening a new market*
4. *Opening a new source of supply*
5. *New organization of an industry, like the creation or breach of a monopoly position*

Introducing a new technology within a company (intended as a product/component never used before in it) or a new production method, necessarily leads to the introduction of a new business approach for that company.

As indicated by Teece, "the essence of a business model is in defining the manner by which the enterprise creates and delivers value to customers and converts payments to profit. To profit from innovation, business pioneers need to excel both at product and business strategy design." [23]

The problem stated in the economic sector is that the Product Business Model, intended as Business built around a unique product, is broken nowadays. An example is given by the cellphone *BlackBerry*, which had nearly 50% market share in 2009, and that share collapsed to 2% in 2013. During last years a shift towards a platform strategy has identified new business apporaches. Platforms draw value from communities and network. The value rises as more people use the platform. An example comes again from the cellphone sector: thinking about mobile operating systems like *Android* and *iOS*, their success has been the externalization of interfaces and the openness to the third party contributions, so the idea worked because users started doing something that the developers did not expect: they created apps and increased company profits [24].

Service-integrated façade is a new envelope concept that many industries and research institutions are investigating in terms of market potential and technical feasibility. By integrating components such mechanical ventilation units, heat exchangers, solar thermal collectors or photovoltaic panels in façade, new interfaces are created. These interfaces are both material and immaterial. In [25], the authors agree on the need to define the interfaces between components. How should components be attached, where do pipes and cables run and who is actually mounting these? In the meantime, designers and façade manufacturers also need to tackle immaterial interfaces: Who is responsible for the process, the maintenance and warranty? In which way the new products should be communicated to the market and how can decision makers be approached. Building integrated systems solutions have to be discussed between building stakeholders during the early design stage, because their introduction has an influence on all involved disciplines.

As stated by Tilmann Klein [2], the question about the risk and failure potential in the façade design process is still open. "A risk analysis for the different stakeholders would be worth a complete separate research. So far, façades have seen a slow and continuous adaption and improvement, which never raised fundamental questions and thus prevented revolutionary changes."

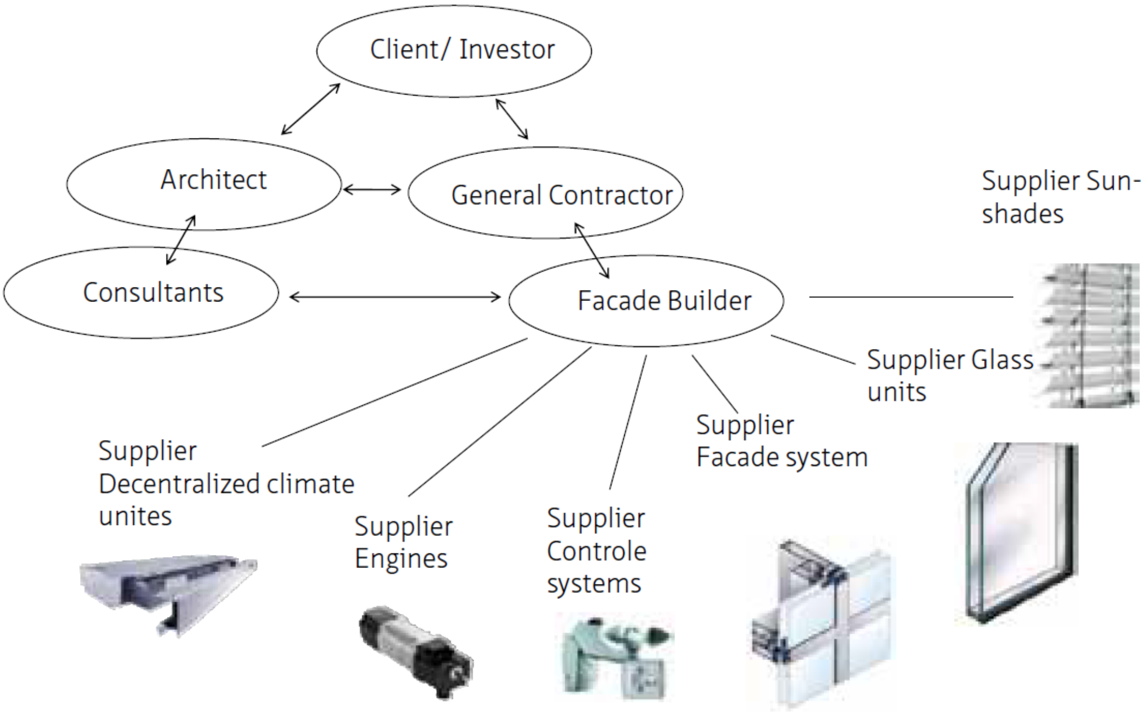


Figure 8 - Scheme of relationship between façade stakeholders [2]

According to the scheme in Figure 8, there is no direct connection between the architect and the façade builder. However, there is an intermediary between them: the façade consultant. This figure is still absent in some markets like the Italian one. The scheme makes clear that façades are composed of highly developed system products. This number of system products is doomed to increase if adaptive technologies and building services will be attractive in terms of façade integration. Architects typically take decisions on these components, but at the same time, they do not have full detailed knowledge of them. The architect needs to reinforce his role as figure in charge of judging the effect of façade functionality and performance.

Prediction of the building performances and the need of a faster process able to answer to the short construction durations are among the main aspects to be considered in order to build a business concept for complex façade systems.

According to Teece [23], "a business model is not a spreadsheet or a computer model. It is a conceptual, rather than financial, model of business based on assumptions about customers, the behavior of revenues and costs, the changing nature of user needs and competitor responses. The concept behind a business model has no established theoretical grounding in economics or in business studies."

Maurer et al. [26] highlight the importance of design parameters when it comes to BIST systems. These are subdivided in Physical, Technical and Non-technical. Technical parameters are easily identifiable in the materials and components, while physical and non-technical parameters might be less deducible. Solar radiation, optical properties, heat transfer, hydraulics, vapor transfer, degradation and possibility to connect PV are the seven *physical* design parameters. Advantages of prefabrication and integration into the building process, software development and simulations, possible economic scenarios of the whole renewable and building market are all *non-technical* parameters.

Plumbers, electricians, architects, building owners, students and financers need data to understand the potential of active façades. However, they also need to know issues differently. Financers do not need to know where valves and tubes are located in the façade and plumbers do not need to be aware about the riskiness of investment, but both of them are necessary to promote new products. One difficulty for newcomers is finding a rough estimate at an early stage. A user-friendly tool to estimate all relevant numbers could help a lot and build on already existing tools.

To favour the development of active façade concepts, the ideal scenario is the designer investing on his project to realize it. Designers and façade builders are the main innovators in this sector but they do not have the capital to carry on ideas. For this reason, a financial model favouring the flux of money from those who have it to those who can materialize the concept is needed. The tool presented in the fifth chapter of this work is the communication medium between innovators and investors: designer and façade builder propose an idea (based on performance data and involved costs) to the investor, who can consider the feasibility of the concept.

One of the obstacles for the designers in considering these solutions is the lack of knowledge about the building physics. Neglecting the heat transfer of solar façades towards the indoor space can mislead the results. New software are required for optimizing the hydraulic layout including the position of valves, pumps, ducts over the façade. Limitations come also from materials. For example, the current exterior insulation and finishing systems (EIFS) cannot withstand the high temperatures of highly selective absorbers behind a glazing. One solution for this problem could be the design of collectors working with a moderate maximum temperature of the absorber. Such solutions could also use inexpensive materials like polymers [26].

In the project Aktifas [27], coordinated by Frauhnofer ISE, they noticed that an improvement of single components of solar thermal collectors (e.g. glazing or absorber) might have a limited potential to reduce the finale price. Products combining mass production and a high degree of flexibility would attract more architects and skilled people. Only holistic approaches to the technical obstacles will lead to economic success.

Zhang et al. [28] suggest the analysis of the market potential as crucial for the development of Active Solar Thermal Façade (ASTF) products. Solar technology is expected to provide nearly 50% of the low-and-medium temperature heat within the EU by 2030. The authors highlight that a firmer market for BIST technologies is possible with the:

- *development of an integrated database/software enabling both architecture design and engineering performance simulation;*
- *real-time measurement of the ASTFs integrated buildings on a long-term scheme;*
- *economic and environmental performance assessment and social acceptance analysis;*
- *dissemination, marketing and exploitation strategies study.*

Approaching the business by taking into account all of these aspects is necessary. There are three backbones supporting a business concept for solar façades: the technology analysis, the cost analysis and the energy performance analysis. Figure 9 shows how these analyses interrelate.

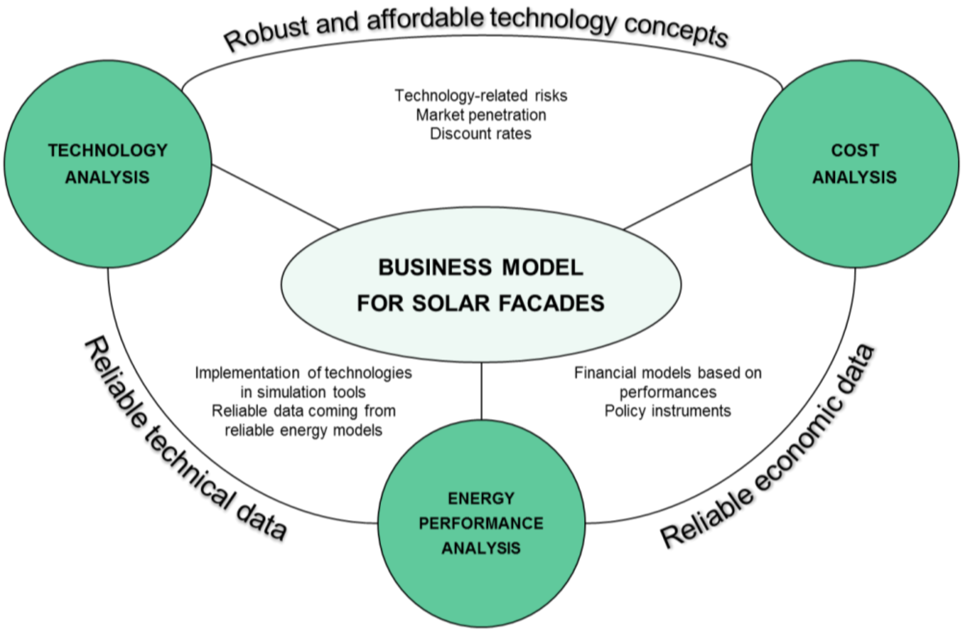


Figure 9 – Identification of the elements supporting a business concept for solar façades and relations

Approaching a business concept this way should clearly communicate to the stakeholders:

- *the real cost of the façade (considering risks, advantages and the whole intervention – a solar façade has to be compared not only with a standard façade but with a façade+heating system);*
- *how the bigger initial investment is paid back (own investment; presence of incentives to pay back the mortar; energy savings to pay back the loan; more useful space due to less or smaller machines inside the building; less on-site works; higher building value; higher rents; the exploitation of the envelope);*
- *the performances of the façade over time (energy production and saving potentials)*
- *the responsibilities between involved parties*

How to capture value from innovative façade systems? Technological innovation without a commercialization strategy can only lead to the self-destruction of the enterprise segment dealing with it. There are two extreme modes by which capturing value from innovation [23]:

- *INTEGRATED BUSINESS MODEL, in which an innovating firm bundles innovation and product together, and assumes the responsibility for the entire value chain including design, manufacturing and distribution. A right asset inside the company is necessary.*
- *PURE LICENSING BUSINESS APPROACH, valid only if one has strong intellectual property rights.*

In between there are hybrid approaches. One situation where there are serious value capture problems is investment in basic research. This usually ends up in science publications, so it is hard to secure intellectual property protection. As a result, it is difficult to charge for discoveries, even if they have the potential to generate high value for society. For this reason, very few firms invest in basic research, and governments fund most of the researches.

One of the major difficulties in developing and promoting solar façades is the shortage of the interactions between the architects and engineers during the integration process. An interactive platform enabling communication between architects and engineers should be able to create such an opportunity. The outcome of this research project is a tool allowing designers, façade builders and investors to discuss decisions around the same table at the beginning of the design process in order to get synthetic data characterizing innovative façade solutions. A façade configurator allowing to visualize the building's façade suggesting where is more convenient from the economic-technical viewpoint could be the follow-up of this research. Simulations carried out at room level, make easy the composition of a building by joining more rooms, which may have active or passive façade modules.

The scheme shown in Figure 10 synthetizes the connections among the three analyzed backbones of the business concept of solar thermal façades. The intent of this figure is mapping out a possible path to be followed to achieve an affordable solution or at least comparable with other more common scenarios. At the very left and very right of the map, the main errors and uncertainties the developers of the façade can run into are reported. More in detail, during the energy modelling stage, assumptions are necessary to implement the façade energy concept, its physics and the building features. These suppositions can lead to numerical errors, which actually can derive from the energy modelling software as well. On the other side, the cash flow analysis should take into account the energy production performance over time, which is expected to decrease, and the cost of energy that is extremely hard to foresee but crucial to assess the affordability of a façade configuration integrating active energy systems. In order to have better performance data, laboratory tests and monitoring are necessary steps, but again the product developers can experience manufacturing and measurement errors. Finally, the investor profit is by far one of the driving factors and it might be the bigger uncertainty if he/she is not adequately convinced. The same approach can be generalized to photovoltaic integrated façades.

In [25], several researchers in the field of the building envelope asked themselves if in the future, nonprofessional clients will be able to erect complex façades. The answer is yes, perhaps a substantial business opportunity within the do-it-your-self range. Obstacles to this kind of 'thinking out of the box' lie primarily within the conservative construction industry. Therefore, it is paramount for product developments like these to have the industry on board from the start.

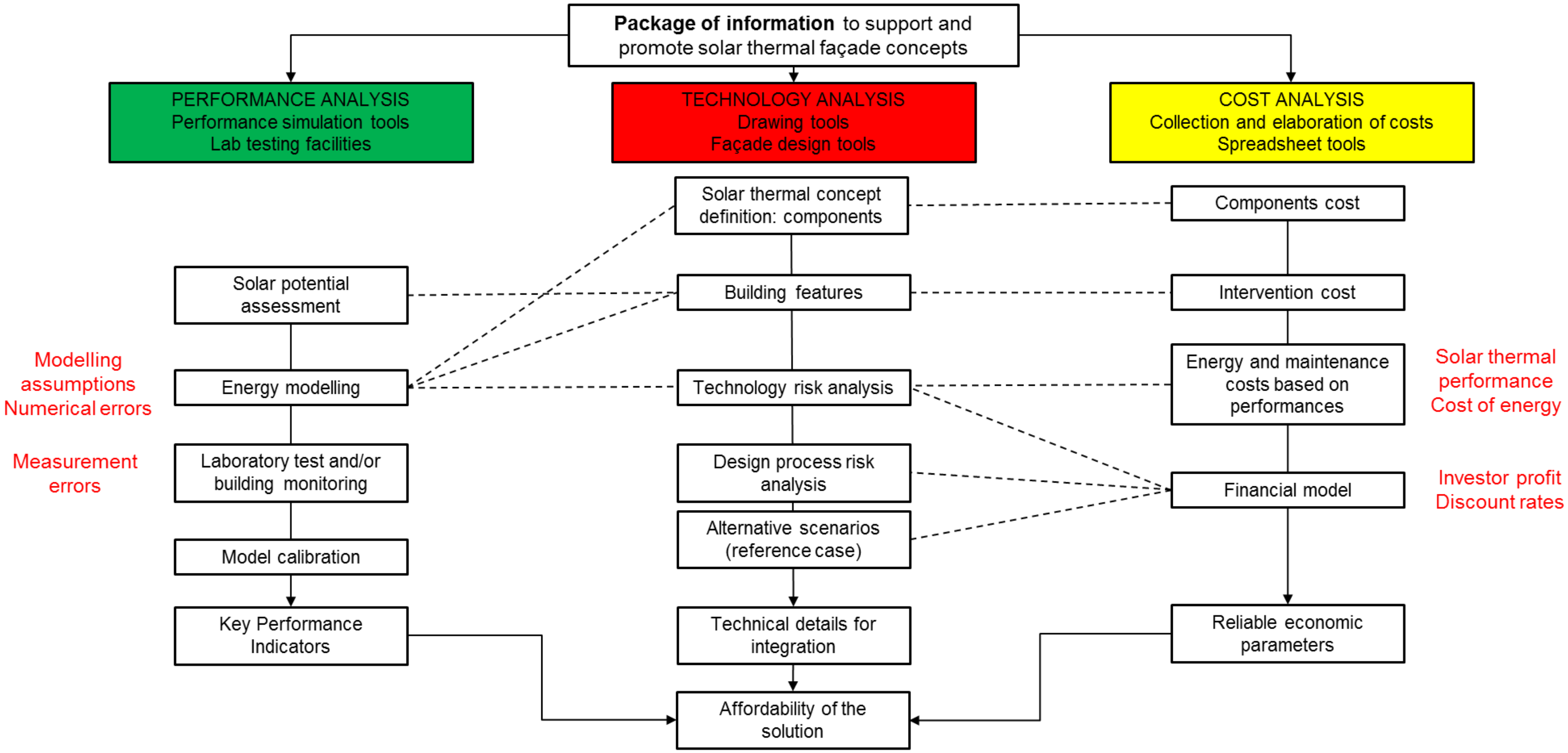


Figure 10 - Steps to analyze the potential business of solar thermal façade concepts supporting the design and the market penetration

1.4 Objectives

The main goal of this research project is understanding the potential of solar façades by developing a multi-disciplinary tool supporting the potential business concept behind solar envelope. The instrument can support the decision process involving designers, façade consultants and investors during the early design stage. Research and Technical Development (RTD) needs are reported.

The instrument is called FAST-IN tool, where FAST-IN stands for Feasibility Assessment of Solar Technologies INtegration. The tool illustrated in the thesis is an original instrument allowing designers, façade builders and investors to assess the economic impact over time of several design choices in terms of technology, maintenance and economic parameters variation. Technologies refer also to passive façade solutions and energy systems. FAST-IN tool provides also energy performance indicators based on dynamic calculations.

This work has been motivated by the lack of awareness, among façade stakeholders, about the potential role that building integrated service façade systems may have in a couple of years. Indeed, the achievement of energy targets could be realistic only if the building envelope will be considered as energy delivery system reducing the size of centralized systems. Only few façade builders are considering integration of active components into façade systems in order to be ready from the technology and market point of views when it will be the moment. The beginning of 2020, when new buildings will have to fulfill the nZEB target, might be this moment. Hence, not so far from now.

A façade concept under development within a project co-funded by the Province of Bolzano, was used as solar thermal façade case study to build and apply the proposed methodology to assess the affordability of BIST façades. More specifically a unitized façade for office buildings fulfilling three extra functions, energy production, energy storage and energy distribution, was analyzed. The integrated components are:

- *a standard solar thermal flat plate glazed collector*
- *an insulated water storage located behind the solar thermal collector*
- *a radiant panel system with aluminum cover installed in the inner side*

All of these components are located into the bottom opaque part of the façade module.

This façade can cover almost the entire demand of energy for domestic hot water, which is low in office buildings, and contribute to reduce the heating space energy consumption. Thanks to the integrated radiant distribution system, the façade is used as terminal both for heating and cooling mode. A key aspect in approaching the business concept of a solar façade is the evaluation of the avoided costs in comparison to a standard solution. For example, the installation of fancoil units may be avoided, and comfort of people working close to the façade can be even higher since no air convection is present.

The assessment of the façade system goes through:

- *A technology analysis to understand risks during the design process and requirements*
- *An economic analysis to identify avoided and extra-costs in comparison to passive façade systems, and to investigate on possible support schemes*
- *A performance analysis focused on energy aspects and the influence of the solar thermal façade on the energy uses and thermal/visual comfort*

The three analyses are the backbones of the business model, giving all the necessary data to consider solar thermal façades at least as an alternative to achieve building energy targets during the early design process. The developed Excel tool is an instrument collecting all the data, and it works as common language source for the involved people. This common language providing to designers the freedom to decide where to install solar thermal façades, giving to the façade builder the inputs to set the façade layout, and offering to the investor financial strategies based on the façade performance, is the core of the developed tool.

1.5 Outline

After having introduced the current development of façade systems, the role of solar thermal façades and the importance of business concepts to promote innovative energy solutions, the solar thermal technologies are better investigated.

In chapter 2, the state of the art of solar thermal technologies, their applications on façade and the marketing achieved during the last years are discussed. A comprehensive analysis of the barriers between research and market penetration of solar façades is reported. Requirements, standards and performance indicators, which can be applied to this specific façade sector, are finally illustrated and commented.

Within chapter 3, the façade case study is first described, and then the interaction between possible risks during the design process and the costs is hypothesized. Specific technology and cost analyses are carried out to understand where the potential for cost reduction is located and if the extra cost respect to a passive façade can be paid back in a reasonable time.

Chapter 4 faces the building physics of the façade system. More in detail, an introduction on the modelling of BIST façades is reported, followed by the proposed methodology to assess the performance of solar thermal façades through an energy model and consequently the affordability, based on calculations over time. Hence not just related to the initial investment.

The data collected in the chapters 2, 3 and 4 were used to build the FAST-IN tool, which is the subject of chapter 5. In this tool financial models linked to the obtained energy performance results are presented.

Finally, a summary and discussion of the work is reported in chapter 6.

Chapter 2

2 Solar thermal technologies and BIST façades

A short introduction related to the idea of integrating solar thermal technologies into façade is here reported. The needs of research and development in the field of solar thermal façades are then highlighted. More in detail, the lack of technical data, the high cost of investment, the need of skilled figures to perform energy simulations and the absence of user-friendly tools to assess the performance of complex façade systems and to create a common language between façade stakeholders, are discussed. Requirements and standards, giving some fundamentals to create a product standard for solar thermal façades, are analysed.

Keywords: solar thermal market; solar façades; design approach; energy performance indicators

2.1 State of the art of solar thermal systems suitable for building integration

The state of art of possible solar thermal technology components, regardless the chance to be integrated into a façade system, is here reported. Solar thermal façade products coming from industrial and research attempts are also showed.

Regardless the place of installation, roof or façade, technologies used to produce thermal energy are basically classified depending on the heat transfer fluid. Usually the heat transfer fluid used in solar thermal technologies is water (mixed up with glycol) or air, which circulates through pipes and distributes the thermal energy captured by an absorber. Various designs of collectors are employed in order to concentrate the solar radiation on the fluid duct and to maximize solar gains. The amount of heat energy captured typically ranges from 300 to 800 kWh/m²y depending on latitude and exposure.

O'Hegarty et al [20] categorized Solar Thermal Collectors into five core types that are the technologies, which most Solar Thermal Façades currently available derive from. These are:

- *Unglazed Collectors (UC)*
- *Glazed Flat Plate Collectors (FPC)*
- *Massive Solar Thermal Collectors (MSTC)*
- *Evacuated Tube Collectors (ETC)*
- *Concentrated Solar Collectors (CSC)*

The paper provides useful equations to calculate the efficiencies of the different collectors, when integrated into façade. Many possible locations of installation are pointed out: opaque façade area (FPC/UC/MSTC), balcony (ETC/FPC), transparent façade area (FPC/ETC), louvres (FPC/ETC) and gutters (FPC).

Cruz Lopez [3] classified solar thermal collectors by distinguishing them in air-based and water-based technologies, which is the categorization the following list is based on.

Air-based solar thermal collectors for heating

Solar air collectors can directly heat a room or can pre-heat the air that passes through a heat recovery ventilator or an air coil of an air-source heat pump. Another frequent application is the crop drying.

Advantages of these systems are linked to the absence of problems associated with corrosion, freezing and overheating. This means less maintenance over time since liquid is the main cause of upkeep. On the other hand, air is a less efficient heat transfer medium than liquid; therefore, air-based systems operate with lower efficiency.

The global solar air heating industry was born thanks to the *SolarWall* technology, considered among the best inventions and engineering feats of the past two centuries [29].

Glazed flat-plate collector

It is best suited for moderate temperature applications ranging from 30° to 70°C, and for applications that require heat during the winter. It is mainly used to heat dwellings. The glazing of the collector helps to prevent losses, while the solar radiation goes through it and reaches the absorber [3], [30].

Unglazed perforated plate collector

It is a collector made of a perforated cladding. Air passes through the holes in the collector before it is drawn into the building to provide preheated fresh ventilation air. Efficiencies are typically high because the collector operates close to the outside air temperature. The most common application of this collector is for building ventilation air heating. Other possible components for this system are: a 20–30 cm air gap between the building, a canopy at the top of the wall that acts as a distribution manifold, and by-pass dampers so that air will by-pass the system during warm weather. Systems have been installed in South America and Asia for drying of tea, coffee beans, and tobacco. Because they require no glazing or insulation, transpired air collectors are inexpensive to manufacture [31]. These collectors are suitable for temperatures below 30°C. The system is architecturally versatile. It can be styled, shaped, and designed in a variety of colors.

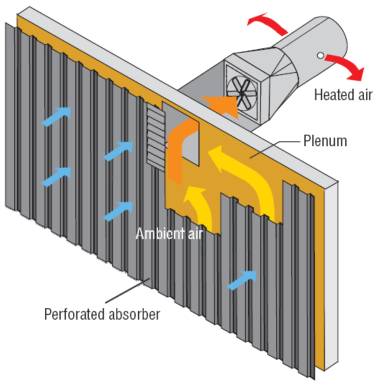


Figure 11 - Transpired Air Collectors for Ventilation Preheating (source: National Renewable Energy Laboratory - DOE)

Back-pass solar collector

This collector consists on an absorber or thermal mass material that absorbs the solar radiation. Outside air generally enters from the top of the non-perforated metal solar cladding that is being heated by sunlight. This technology has a lower cost than transpired collectors [32].

Trombe wall

A Trombe wall consists of a vertical wall, built of a material such as stone, concrete, or adobe, covered on the outside with glazing. Sunlight passing through the glazing generates heat, which conducts through the wall. Warm air between the glazing and the Trombe wall surface can also be channeled by natural convection into the building interior or to the outside, depending on the building's heating or cooling needs [33].

Liquid-based solar thermal collectors for heating

These systems use electric pumps, valves, and controllers to circulate water or other heat-transfer fluids through the collectors. Once the liquid has passed through the collector and it has been heated, it runs into a storage tank or a heat exchanger for immediate use. The flow rate through the collector should be between 0.82 and 1.22 liters per minute per square meter of collector (in the case of water). Glycol might be mixed up with water in order to prevent the freezing. Typical liquid-based STCs are glazed flat-plate, unglazed flat-plate and evacuated tubes.

Depending on the climate and the size of the load, three systems can be identified:

- *Open-loop systems use pumps to circulate water through the collectors. These systems are appropriate in areas that do not freeze for long periods and do not have hard or acidic water.*
- *Closed-loop systems, which pump heat-transfer fluids such as a mixture of glycol and water antifreeze through collectors. Heat exchangers transfer the heat from the fluid to the water stored in the tanks. During summer sunny days, the fluid has to circulate continuously to avoid stagnation.*
- *Drain-back systems, using pumps to circulate water through the collectors. Because the water in the collector loop drains into a reservoir tank when the pumps stop, this is a good system for colder climates, but higher energy consumption might be required to reactivate each time the water loop. Big centralized water storage tanks are necessary to collect all the fluid when the system is switched off.*

Glazed flat-plate collector

This technology consists of a dark flat-plate absorber, a glazing that enables radiation to go through but reduces heat losses, a piping network where the liquid flows in to remove the heat from the absorber, and an insulation layer in the back. Everything is fitted in an aluminum housing.

The sunlight passes through the glazing and strikes on the absorber, which is made of a high transmittance material that has a high-absorption coating. Tubes filled with heat-transport fluid (risers) run vertically through the absorber and once the fluid heats up, it exits the collector and transfers the heat to an insulated water tank to store it by means of a heat exchanger. The risers are connected at both ends to a manifold or header, which works as inlet and outlet of the fluid. The absorber plate can be a single sheet on which all risers are fixed or each riser can be fixed on a separate fin. Each riser can be welded to the absorbing plate or they can be an integral part of the plate [3].

Lately, new materials have been promoted to be used as absorber plate to make solar collectors lighter and more sustainable. Among these, there is polymer. Attention has to be paid when using collectors that have polymer absorbers because they can melt if stagnation temperature is reached. On the other hand, metal absorbers and tubing can be cracked if not drained on freezing periods.

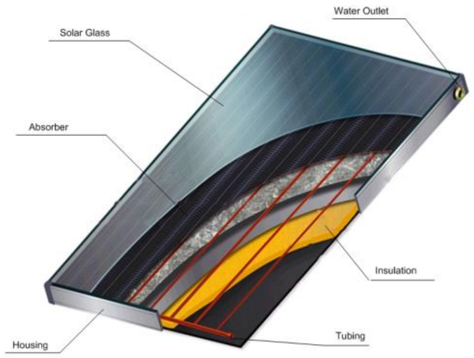


Figure 12 – Glazed flat plate collector (source: http://www.freehotwater.com/)

Unglazed flat-plate collector

Because they are not insulated, these collectors are best suited for low temperature applications where the demand temperature is below 30°C. By far, the primary market is for heating outdoor swimming pools, but other markets exist including heating seasonal indoor swimming pools, pre-heating water for car washes, and heating water used in fish farming operations [34].

Evacuated tube collector

This collectors use liquid-vapor phase change materials to transfer heat at high efficiency. They consist of parallel rows of evacuated glass tubes that feature a fin attached to a pipe inside, which takes the heat out of the collector. The vacuum reduces the heat loss through conduction and convection; therefore they can reach higher temperatures that those of the flat plate. The advantage of this collector is that the circular profile of the tube will always be perpendicular to the sunrays, and therefore, the energy collected is almost constant throughout the daytime [3].

Figure 13 - Evacuated Tube Collector [35]

There are two types of evacuated-tube collectors:

1. *Direct-flow and heat pipe. The direct-flow evacuated-tube collector has a flat or curved aluminum fin attached to a metal or glass pipe. This fin is covered with a selective coating that absorbs radiation. The heat-transfer fluid runs constantly through the pipes and takes the heat from the fins.*
2. *The heat pipe evacuated-tube collector consists of a heat pipe to which is attached a black copper absorber fin inside a vacuum tube. The heat pipe contains a small amount of fluid (e.g. methanol) that undergoes an evaporative-condensing cycle. In this cycle, solar heat evaporates the liquid and the vapor travels to the condenser region, where it condenses and releases it latent heat. The condensed fluid returns to the collector for the process to be repeated.*

All the mentioned technologies are characterized by different efficiencies, which vary dynamically according to environmental and operating conditions. It should be also noticed that efficiency may be referred to different surface areas: gross, aperture, absorber. Aperture, Absorber and Gross measurements may also differ between test labs and countries based on their definitions. Most of countries and industry associations have adopted aperture as the standard surface area to use when quoting efficiency values. Regarding the aperture area of flat plate collectors, this is calculated as the glazing area exposed to sunlight, while for evacuated tube collectors, is the inner diameter of the clear glass tube. Figure 14 sums up the main solar thermal technologies by specifying the efficiency, calculated on the aperture surface area, as function of the temperature difference between collector and ambient temperature. Operating temperatures and achievable efficiencies determine the potential use of a technology to cover specific loads.

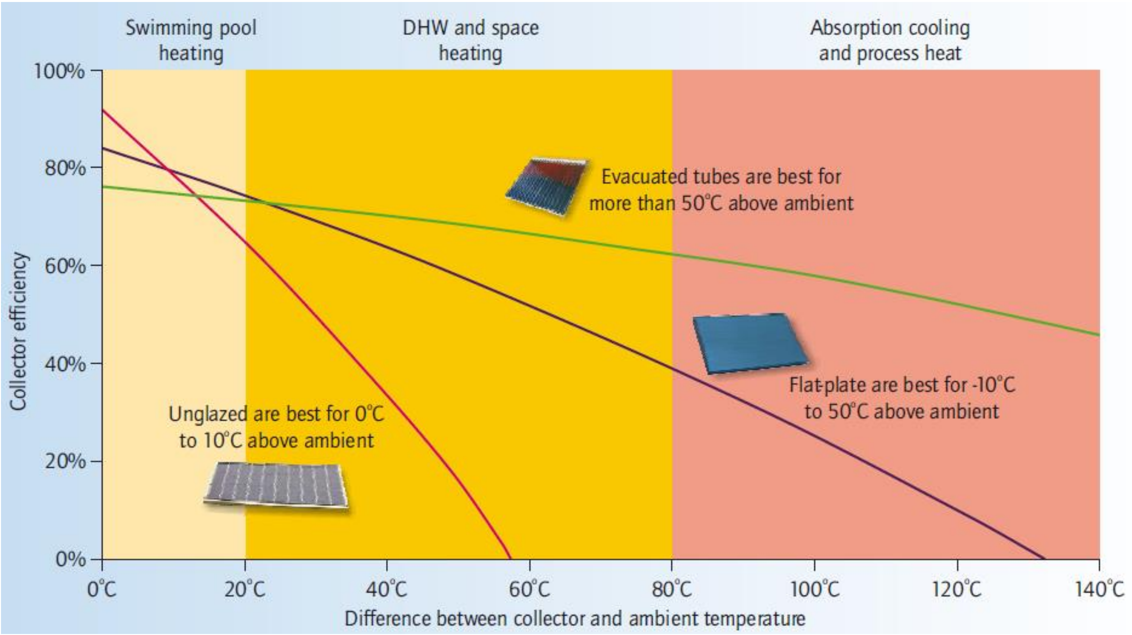


Figure 14 – Collector efficiencies at different temperature differences [36]

Solar thermal collectors for cooling

During last years, the energy consumed for cooling purposes has increased. To reduce the primary energy consumption of chillers, thermal cooling systems offer interesting alternatives especially for energy that comes from solar thermal collectors. An advantage of solar-assisted cooling technologies is that peak cooling demands often correlate with peak solar radiation, which makes them suitable for inexpensive cooling production [3]. There are two main technologies suited for this scope: absorption cooling and desiccant cooling.

Hybrid Solar Heating Systems

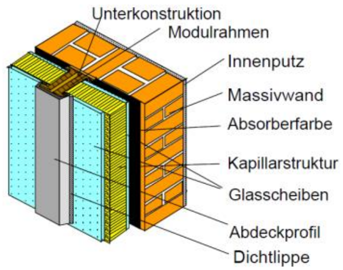
Another way to increase the share of renewable energy in household energy consumption is a combination of solar thermal systems with heat pumps or solar PV systems. Solar-assisted heat pumps would use solar thermal systems to reduce the temperature lift required for the heat pump, thus improving its performance and efficiency. Photovoltaic/solar thermal hybrid (PVT) systems first use solar PV panels to convert sunlight into electricity; then heat absorbers in the back of the PV panel to cool down the cells and use the heat for water heating [37].

In the last 15 years, researchers and manufacturers have tried to join solar thermal collectors and façade systems in order to get integrated products better known as Building Integrated Solar Thermal façades. Since a fluid (air, water or water-glycol) circulates inside the active elements, heat and mass transfer characterize these façade systems. However, it is not allowed to know if final products succeeded or failed, and in case of failure why and when (from production to operation after the installation). Once more, it is difficult to find public information. It is interesting coming to know that some industries have gone beyond the mere integration of a solar collector into the façade. For example, the Austrian prefabricated façade builder *GAP Solutions*, among its solutions, proposes the installation of a production-distribution system. Indeed, as shown in Figure 15, they can install on façade a piping system to distribute the energy produced from the façade directly to the building.

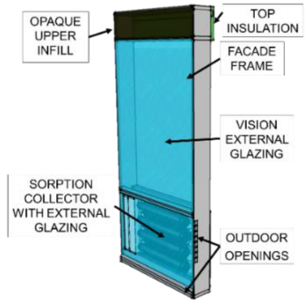
Figure 15 - Distribution system applied to the existing façade (source: AEE Intec, 2012)

A list of active façade solutions integrating solar thermal technologies or used to collect heat, is summarized in the below table. Some of these items are products currently available on the market, some are just case studies under development. The technology readiness level (TRL) is also specified. Where available, prices are showed, but still it is not clear what is included within it. Other products can be found on the web but usually they lack information. For this reason, a short list was preferred.

Table 1 – Solar Thermal Façade solutions

#	Product/Manufacturer	Technology description	Project/Application	Year	Cost [€/m²]	Figure	TRL
1	Transparent Thermal Insulation Panels (TWD) [38]	Passive solution allowing to collect energy thanks to transparent insulation panels (Plastic, Glass, Silica-Aerogel). The system can be provided with a wooden frame protected by aluminum profiles or with aluminum frame.	N.A.	2000	400-650 (wooden) 450-750 (aluminum)		9
2	Passive solar façade by *Lucido® Solar* (wooden absorber behind a glass pane) [39]	The Lucido® system consists of a solar glass and a wood absorber, which are separated by an air layer. The system can be installed on any supporting structure.	http://www.lucido-solar.com/referenzen/projekte/	1999	400-500		9
3	GAP:skin: Passive module by *GAP solutions* [39]	This is a wooden-frame façade system, which offers the possibility to integrate different components: mechanical ventilation, heat collectors, PV or simply a tempered air cushion.	http://www.gap-solutions.at/en/references/references/	2006	600 (including new windows)		9

4	GAP:water: Active module by *GAP solutions* [39]	This is a wooden-frame façade system, which offers the possibility to integrate different components: mechanical ventilation, heat collectors, PV or simply a tempered air cushion.	http://www.gap-solutions.at/en/references/references/	2006	N.A.		9
5	Thermo-active components produced from UHPC concrete by *Fraunhofer ISE* [40]	Façade prototype integrating ultra-high performance concrete to distribute heated water.	Laboratory phase	2012/2014	N.A.		4
6	BIST façade - VarioSol E collectors by *WINKLER SOLAR* [41]	Customized solar thermal collector system for every building shape and position. See also paragraph 2.2 for further information.	http://www.winkler-solar.com/solar-façades.html	N.A.	250-300 (from the manufacturer)		9

7	Solar Thermal Glass by *Robin Sun* [42]	Glazing system integrating solar thermal absorber stripes. The system can be adapted to many frame materials (Wood, Wood-Aluminum, Aluminum, PVC)	N.A.	N.A.	N.A.		9
8	Façade integrated sorption collector *by Climate-Well, Tosoni and EURAC*	Curtain wall (aluminum frame), stand-alone air-based solar heating and cooling system (only for space heating and cooling) integrated in the façade spandrel. Solar thermal collector realized with vacuum tubes. Aeraulic box on the back with dampers and fans.	FP7 Inspire project prototype	2012-2016	300		4
9	SolarWall by *John Hollick* [29]	Kind of ventilated façade working as solar air heating system producing preheated air. The PV/T solution is available as well.	Several all over the World (http://solarwall.com/en/case-studies.php?dgp=1#system)	1980s	300		9

2.2 Solar thermal market

In this paragraph, a market analysis of solar thermal collectors and products developed for the integration into façade is carried out. The evolution of the solar thermal market in Europe gives a general frame of the state of the art of solar thermal collectors. Existing products studied for the integration into façade and solar façade systems are illustrated by trying to understand if there has been any strategy to market the solution. Integration issues are discussed. Application examples are reported as well. The need of a building integrated design is also highlighted.

Solar thermal is the most mature technology among all currently available solar technologies. Indeed, it has relatively higher solar conversion efficiency, 2 to 4 times higher than PV systems [43]. Concerning the European Photovoltaic market, the decline in recent years of European markets that performed well (Italy, France, Germany) has decreased the new installed capacity: in 2012 the installed capacity was increased by 33.6% with respect to 2011, but in 2013 only a 15.5% increase was stated in comparison to the cumulated capacity installed in 2012 [44]. With regard to the importance in the world, in 2011 the European PV market covered 70% of the worldwide market, while in 2014 the share decreased to 50%. This phenomenon was due to the cessation of support policies [45]. On the other side, smaller-sized markets such as Switzerland, the Netherlands, Austria, and Belgium are still showing progress.

With reference to the European Solar Thermal market, a cumulative capacity of 32,987 MW_{th} was installed in 2014, corresponding to more than 47 million m^2 of solar thermal collectors [35]. According to the European Solar Thermal Industry Federation (ESTIF), in 2014, the annual rate of installed capacity decreased by 7.1% [46]. The European solar heating market continues to suffer from the contraction of sales in its largest markets, having reached the same market level as in 2007, before the peak year of 2008. This trend is shown in Figure 16. There are several main factors behind this sluggish performance, such as the low gas prices, difficult access to finance for consumers, slow-moving construction sector, less public support schemes for solar thermal. The solar thermal sector also suffers from competition from alternative technologies (sanitary hot water heat pump, condensing gas boilers, and so on) that are also eligible for incentives and offer cheaper installation costs. It has not be neglected that also solar photovoltaic can address the domestic hot water and space heating segment, especially when coupled with heat pumps.

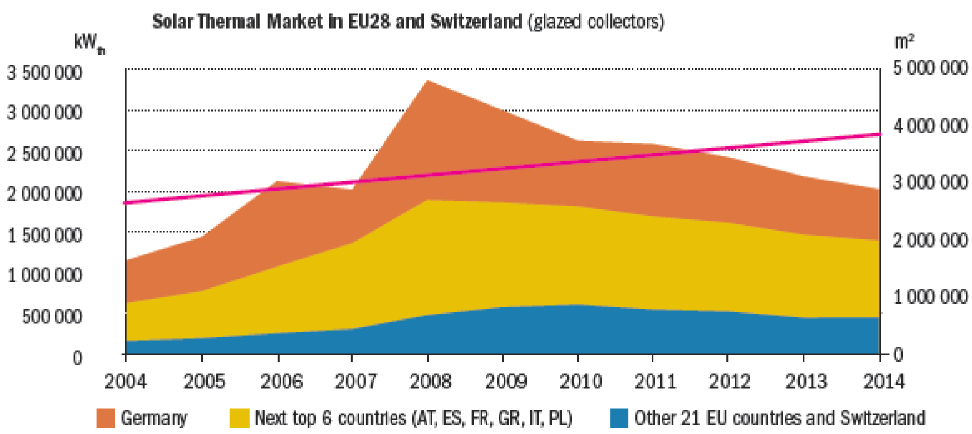


Figure 16 - Solar Thermal Market in EU28 and Switzerland [46] (1 m^2 of solar thermal collector area corresponds to 0.7 kW_{th})

In terms of economic significance, the solar thermal sector reached a combined turnover of 2 billion euros in 2014. The single-family housing segment still represents the bulk of the solar thermal market. In some countries there is a trend for smaller average-sized individual installations. For example, the average size of individual systems in Germany is now around 5 m² (3.5 kW_{th}) for domestic hot water systems and 12.5 m² (8.8 kW_{th}) for combi-systems [46]. In the year 2006 about 25,000 people were working in the solar thermal sector (production, installation and maintenance). If the goal to install three kW_{th} (4 m²) per inhabitant in Europe (EU 27) can be reached and if an increase of productivity is taken into account, the people employed in the solar thermal sector will rise to 240,000 by 2020 [47].

About the technologies, flat plate collectors remain the favorite solution with an annual market share of 88% in 2014. As reported in Table 2, both flat plate collectors and vacuum collectors were subject to a contraction in comparison with the 2013 market. A slight increase (0.6%) was stated for unglazed collectors.

Table 2 - Annual installed solar thermal surface in 2014 in EU28 [Source: EurObserv'ER 2015]

TECHNOLOGY	Surface area [m²]	Share	Variation Vs 2013
Flat plate collectors	2,587,438	88.3%	-1.5%
Vacuum collectors	246,135	8.4%	-22.6%
Unglazed collectors	95,495	3.3%	0.6%
Total	2,929,068	100%	-3.7%

The role of solar thermal installations of covering future energy needs has been set as crucial. The European Commission launched the Renewables Progress Report, which shows that the 2020 indicative targets for solar thermal, reflected in the National Renewable Energy Action Plans (NREAPs), are likely to be missed by 41% - 45%. These targets are visible in Figure 17.

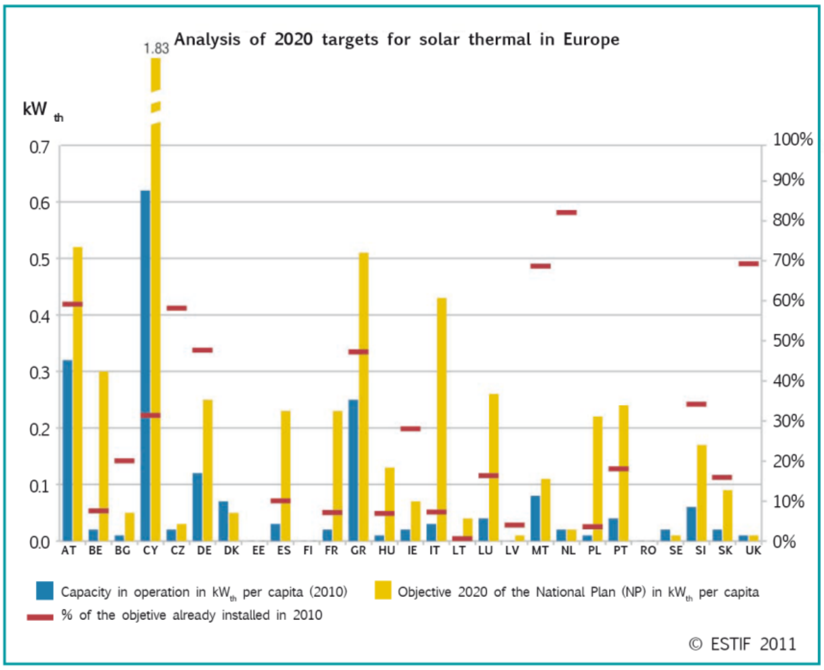


Figure 17 - Solar Thermal installed capacity per capita in 2010 and targets by 2020. Source: ESTIF

As reported by EurObserv'ER [35], incentives and subsidy mechanisms have not worked in the right way during last years. Emblematic is the French case, whose market is in free falling: the government reduced the tax credit rate for individual solar water heaters and combined systems, and favored technologies that already require a lower investment cost like thermodynamic hot waters or condensing natural gas boilers. Furthermore, the last thermal regulation required low renewable energy production performance levels, while a hot water heat pump with a COP just over 2 is enough to satisfy the standard. Austria, in 2014, stated the fifth consecutive fall; in this case the main reasons are the competition from photovoltaic systems and the sharp contraction of the individual homeowners' segment. Indeed, it seems that demand from customers receptive to environmental issues has already been met. Other targets might be necessary. It is not easy to trace possible future trends for the solar thermal market since some countries are growing (Spain), others are falling (France) and some nations are trying to catch up on past levels (Austria).

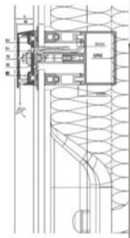
However, according to the RHC Platform, the potential for solar thermal technologies is still high: in 2020 over 25% of heat consumed in the European Union could be generated with renewable energy technologies and by 2030 renewable heating and cooling technologies could supply over half the heat used in Europe [1]. This potential is associated both to usual installations on roof and integration on envelope as roof or façade element. Building-integrated solar thermal systems can offer cost savings compared to a conventional building skin and additional solar thermal collectors. Less material is necessary and only one installation process has to be paid. Even though these quantifiable benefits, BIST systems still have to penetrate the market and architects do not conceive them as an architectural solution.

Countries such as Austria and Germany are keen to see an improvement in the solar fraction of combi-systems: from around 25% to above 50% and even up to 100 %. In well-insulated single-family homes, a solar fraction (for heating and DHW) of 60% can be achieved with a collector area over 30 m^2 with a 6 m^3 hot water storage. A building with a solar fraction above 50 %, namely a *Solar Active House,* is considered one of the three strategically important pathways for solar thermal progress. More than 1000 of these houses have been already built in central Europe [1]. Despite this segment, more reliance should be put on multiple-family dwellings, tertiary and industrial segment activities, aided by the implementation of new thermal regulations. EurObserv'ER also states that another current growth vector is the connection of solar thermal collector fields to existing heating networks equipped with storage pools for the winter season [35]. This technology is already very widespread in Denmark and Sweden, but it is now developing in Germany, Austria, the Netherlands and even in France.

No data concerning the number of BIST installations all over the Europe are available, unlike the BIPV market, for which some studies investigated solutions, past trends and forecasts in the European context [48], [49], [50], [51], [52]. The most complete study about BIST products, their acceptance among designers and applications, is the work carried out by Maria Cristina Munari Probst [18], who investigated on *Architectural Integration and Design of Solar Thermal Systems.*

Shown below are some examples of BIST products characterized by a different level of integration. For each product some features regarding the flexibility of the system, the activities to install it and cost range as indicated by the manufacturers are reported.

Product 1 - Solar flat plate glazed collector for Building Integration

Product's name	**Prisma solar flat collector**
Producer	S Solar
Product category	BIST - Solar flat plate glazed collector
Pictures	   Solar collector Example of application
Main features	Suited for façade glazing systems in aluminium, PVC or wood The solar collector is installed mechanically as an ordinary single pane of glass The absorber is treated with a selective layer of thin film to make the energy conversion more efficient Very high efficiency due to very low heat losses Weight excluding glass is 5 kg
Relevant features for façade integration	Flexibility in size (The dimensions of the façade element is adjusted after the façade proportions as well as the glass thickness in relation to building codes) → maximum size: 1200x2200 mm The color printed at the edges of the glass can be customized No choice for the colour and the surface texture of the absorber Surface of the glass available can be in milky white or transparent Dummies are not available
Building site implementation Complementary Human resources and equipment	Static engineer (structural survey), Installer, Plumber for connections, Architect for integration, Works director (material acceptance) Storage tank, Pump, Tubes and valves, Crane or aerial platform, Linea vita devices
Costs	€/m²(referred to the absorber's surface area)
Included in costs	
Needed extra costs	Water storage, Overall hydraulic connections, Pumps, Control hardware and software

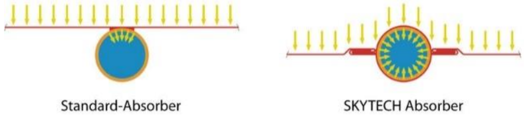
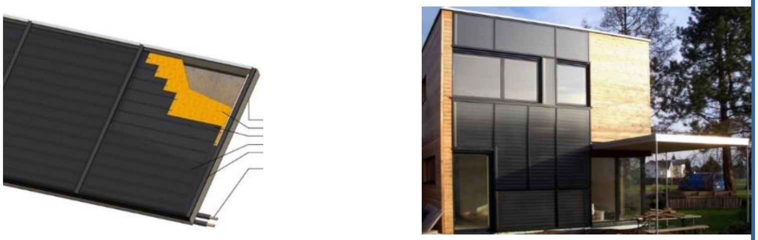
Product 2 - Solar flat plate glazed collector for Building Integration

Product's name	Polymer flat plate solar collector
Producer	AventaSolar
Product category	BIST - Solar flat plate glazed collector
Pictures	 Example of application
Main features	Polymeric based absorber Low weight technology (8 kg/m² without heat carrier) Low manufacturing energy consumption and complete recyclability
Relevant features for façade integration	Flexibility in size (8 formats with a fixed width of 60 cm) No choice for the colour and the surface texture of the absorber Dummies are not available
Building site implementation Complementary Human resources and equipment	Static engineer (structural survey), Installer, Plumber for connections, Architect for integration, Works director (material acceptance) Storage tank, Pump, Tubes and valves, Crane or aerial platform, Linea vita devices
Costs	€/m²(referred to the absorber's surface area)
Included in costs	
Needed extra costs	Water storage, Overall hydraulic connections, Pumps, Control hardware and software

Product 3 - Solar flat plate glazed collector for Building Integration

Product's name	**H+S ThermiePanel 38**
Producer	H+S SOLAR
Product category	BIST - Solar flat plate glazed collector
Pictures	 Example of application  Solar collector  Solar collector in a window
Main features	Low thickness (38 mm) The gap is filled with argon gas Possibility to be installed on usual triple glazing window frames
Relevant features for façade integration	The gluing of the glazing allows the use of any jointing system No flexibility in shape and size No choice for the colour and the surface texture of the absorber Dummies are not available
Building site implementation Complementary Human resources and equipment	Static engineer (structural survey), Installer, Plumber for connections, Architect for integration, Works director (material acceptance) Storage tank, Pump, Tubes and valves, Crane or aerial platform, Linea vita devices
Costs	€/m^2(referred to the absorber's surface area)
Included in costs	
Needed extra costs	Water storage, Overall hydraulic connections, Pumps, Control hardware and software

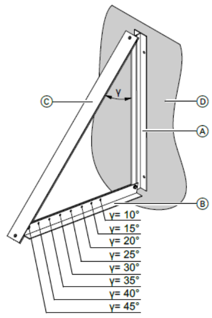
Product 4 - Solar flat plate glazed collector for Building Integration

Product's name	**Variosol E collectors system**
Producer	Winkler SOLAR
Product category	BIST - Solar flat plate glazed collector
Pictures	 Absorber shape  Solar collector and example of application
Main features	In-roof mounting for different kind of materials Façade and balcony installation Available both with reflecting and anti-reflecting glass Reflection reduced thanks to the glass (major energy yield) SKYTECH absorber with a copper tube fully integrated into the copper sheet (360° contact) which leads to an optimized heat transfer to the fluid inside
Relevant features for façade integration	Installation on steel channels Customization Flexibility in dimensions due to the possibility to connect single strips absorber: up to 24 m² in size No choice for the colour and the surface texture of the absorber Dummies are not available
Building site implementation Complementary human resources and equipment	Static engineer (structural survey), Installer, Plumber for connections, Architect for integration, Works director (material acceptance) Storage tank, Pump, Tubes and valves, Crane or aerial platform, Linea vita devices
Costs	250 – 300 €/m²(referred to the absorber's surface area)
Included in costs	Collector
Needed extra costs	Water storage, Overall hydraulic connections, Pumps, Control hardware and software

Product 5 - Solar vacuum tube collector for Building Addition

Product's name	**VITOSOL 200-t type Sp2a**
Producer	Viessmann
Product category	BIST - Heat pipe vacuum tube collector
Pictures	 Solar collector  Example of application
Main features	Solar absorber surfaces with selective coating integrated inside the tubes Condenser totally wrapped (higher efficiency for heat transmission) Rotating tubes (+/- 25°) Dry connection of tubes (substitution also possible at filled plant)
Relevant features for façade integration	Installation on steel channels Special modules for balconies No flexibility in shape 3 dimensions are available No choice for the colour and the surface texture of the absorber Dummies are not available
Building site implementation Complementary Human resources and equipment	Static engineer (structural survey), Installer, Plumber for connections, Architect for integration, Works director (material acceptance) Storage tank, Pump, Tubes and valves, Crane or aerial platform, Linea vita devices
Costs	840 €/m^2(referred to the absorber's surface area)
Included in costs	Collector, Anchoring brackets and channels, Piping, Temperature sensor
Needed extra costs	Water storage, Overall hydraulic connections, Pumps, Control hardware and software

Product 6 - Solar flat plate glazed collector for Building Addition

Product's name	**VITOSOL 200-F type SH**
Producer	Viessmann
Product category	BIST - Solar flat plate glazed collector
Pictures	 Solar collector  Façade mounting system
Main features	Solar absorber with high absorbtance rate and low emissivity Rear side wall resistent to drilling and corrosion Simple fixing system Fast hydraulic connection among collectors
Relevant features for façade integration	Availability of brackets for the sloped installation No flexibility in collector's shape and dimensions No choice for the colour and the surface texture of the absorber Different colours for the frame are available Dummies are not available
Building site implementation Complementary human resources and equipment	Static engineer (structural survey), Installer, Plumber for connections, Architect for integration, Works director (material acceptance) Storage tank, Pump, Tubes and valves, Crane or aerial platform, Linea vita devices
Costs	535 €/m²(referred to the absorber's surface area)
Included in costs	Collector 2.32 m², Anchoring brackets, Piping, Temperature sensor
Needed extra costs	Water storage, Overall hydraulic connections, Pumps, Control hardware and software

These are only a few BIST products that can be found on the web, but it is hard to find related applications and the spread of their use. Another example of active façade, which has found market in the recent years, is a product developed by *GAP³ solutions GmbH*, company located in Austria. Many applications can be observed from the website http://www.gap-solutions.at/en/references/references/. Among the available façade solutions, they propose the so called *GAP:water*, which uses existing waste water heat and focuses on eliminating long lines resulting in heat loss. It is also possible combining concrete storage absorbers, loss-free hot-water distribution, heat recovery and photovoltaic, depending on the needs. The decentralized hot-water supply in the façade prevents distribution and transport losses, it is maintenance-free and requires no regulation expenditure.

Figure 18 – *GAP:water* façade system installed in Austria [Source: IEA Annex 50]

In 2014, within the Task 39 of the Solar Heating and Cooling Program "Polymeric Materials for Solar Thermal Applications", they published a report including different applications of solar thermal technologies into the building envelope. More information can be found at the website http://task39.iea-shc.org/. Here follow just three examples.

1) *Bellona Building, Oslo (Norway)*

Figure 19 – Bellona Building with tilted solar envelope

The Bellona building is an office building with floor space of 3,120 m² over five storeys. The building was built with in situ concrete and façade were then covered with plaster. Solar collectors cover large parts of the south-facing façade and contribute to achieve the energy requirements. The solar collectors heat the water used in the offices and in other buildings nearby. The south-facing façade is divided between inward-facing windows and outward-facing dividers. The outward-facing dividers are perfect for installing solar collectors, 240 in all (291 m²) as showed in Figure 19. Energy is supplied through solar collectors, heat pumps, district heating and electricity. Additional costs were estimated to be 2500 €/m², which is +10% compared to average solution costs.

2) Headquarter AKS DOMA Solartechnik (Austria)

Figure 20 – AKS DOMA HQs; south oriented façade

In this building, the energy and electricity demand for the offices (470 m²) and the production hall (1,380 m²) is covered exclusively from renewable energies. The heat distribution in the office building is performed via a wall heating system. The production hall is heated via a floor heating system integrated in the concrete floor. 80 m² of solar collectors are integrated into the south-oriented façade (Figure 20). A 950 l water heat store was installed and the auxiliary heating is provided by a biodiesel block heat and power plant. The solar system is a combined system, contributing to both domestic hot water preparation and space heating. Solar flat plate glazed collectors (Dimensions: 3000 mm length, 950 mm width) branded AKS DOMA were installed.

3) Group Dion, Quebec (Canada)

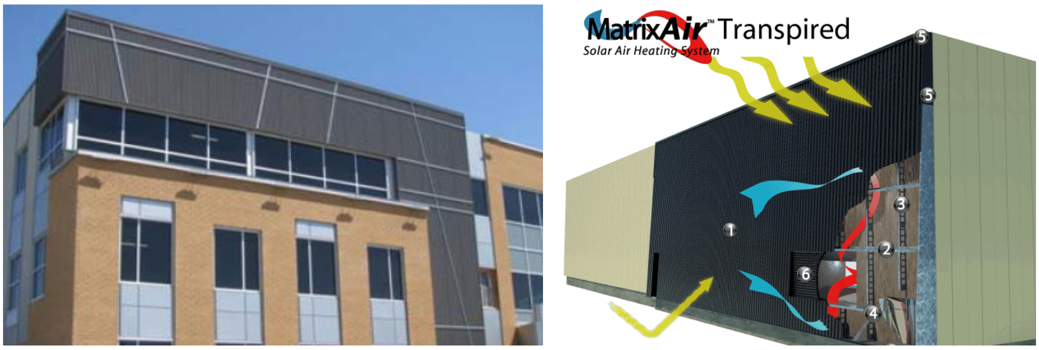


Figure 21 – Group Dion building with MatrixAir TR © façade system

This office building has a façade integrating 90 m² of solar air-based collectors, providing space heating. A particular technology was chosen: the MatrixAir TR (Transpired) solar collector [32] that has demonstrated operating efficiencies up to 70% with payback´s within five years on most of new buildings. The perforated metal absorber is used to draw in heated fresh air off the surface of south-facing walls, where it is then distributed throughout the building as pre-heated ventilation air. The façade operation system is displayed in Figure 21.

2.2.1 Market barriers

Even though good results has been achieved in terms of both performance and technology integration, active façades have not found the right acknowledgement among designers, façade builders, investors and society in general. Technical, economic, process and social related barriers can be identified. In this paragraph, different obstacles to the widespread use of solar thermal façades are described to understand how they contributed to increase the level of uncertainty connected to this technology.

Aesthetic is one of the most feared aspects in using solar thermal collectors in façade. Usual solar collectors have a typical surface finishing, but different patterns are now available thanks to research and innovation projects (Figure 22). Another obstacle is due to the difficulty to substitute current solar collectors with others coming from a different industry; this is a matter of standardization of material interfaces like joints and tubes, which system suppliers should solve.

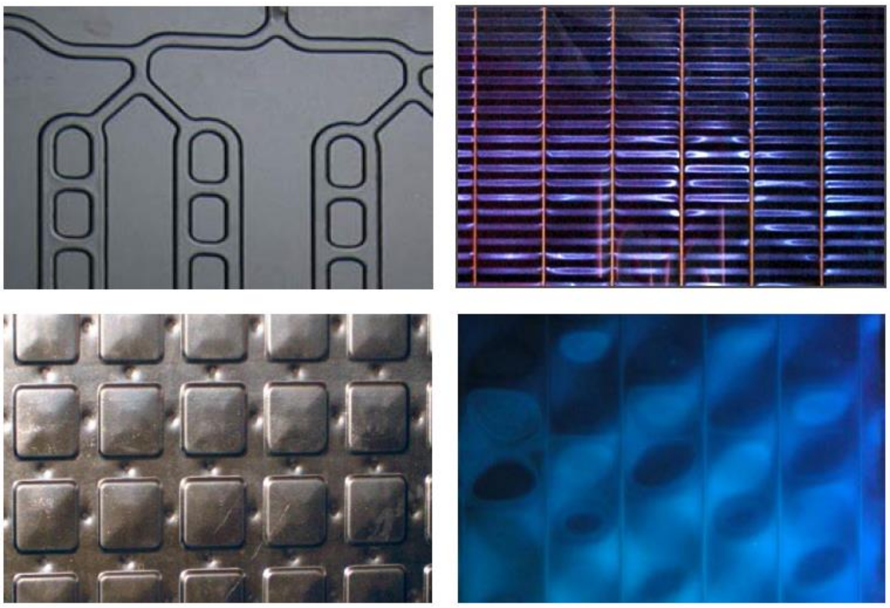


Figure 22 - Different surface finishing for solar absorbers [Source: IEA SHC task 41]

Market barriers in the buildings sector are complex and can be difficult to overcome, so successful implementation of public policies will be essential to achieve high levels of market diffusion. There is a need for integrated and comprehensive policies helping to overcome a range of barriers, such as higher initial costs, lack of consumer awareness of technologies and their potential, split incentives and the fact that the true costs of CO_2 emissions are not reflected in market prices [4].

Germany is trying to carry out the renewable national energy system. Experts from the Fraunhofer ISE showed that energy efficiency cannot be the only answer; more energy production is crucial for a 100% fulfillment. They also showed that the area available on the roofs of the existing building stock is not sufficient. Therefore, also the façade has to be used for solar thermal applications.

Activating the building envelope for solar energy production will be mandatory for new buildings after the year 2020 due to the European Energy Performance of Buildings Directive (EPBD). The solar thermal European market is still far from the technology readiness necessary to spread Building Integrated Solar Thermal façade systems. But, as reported by Cappel et al. [53], different technologies are ready to be used as integrated products: vacuum tubes have been used as balcony balustrades; unglazed or air based collectors are installed as façade systems of industrial buildings; and some glazed façade solutions are possible as showed in the chapter. Customized collectors could be necessary to obtain an acceptable appearance of the building.

Four categories of barriers were considered: technical, process, economic, social.

Technical barriers

Technical barriers are those related to the technology and the building layout.

The wall has to bear the additional structural load of the collector or the absorber and the glazing while thermal bridges should be avoided. Attention is required for active components in contact with passive components. In case of a wooden frame, this can decay or even slowly turn into charcoal, which means lacking safety requirements for the building. Façade collector absorber temperature can easily go over 100°C. Heat transfer through the wall towards inside is 25 W/m² (when collector is hit by solar radiation in March) [19]. Another obstacle is linked to the bigger influence of the surroundings on the performance; indeed, façade collectors can be shaded more frequently in comparison with roof installations.

The direction of vapor transfer can change because the outer layer of the wall is heated and reaches high temperatures. In this case, vapor should be able to exit the wall to the interior of the building. This is why the inner layers should be more open to diffusion for integrated systems. The measurements of Bergmann and Weiss on a wooden and a concrete test façade did not reveal any critical condensation in any layer behind the glazing or the absorber [53].

Concerning the hydraulic connections, the most convenient configuration is the *Tichelmann* interconnection, in which identical arrays with the same number of serially connected collectors are connected in parallel. Especially in retrofit, one has to face the problem that collector arrays might have different sizes, demanding a complex design for the hydraulics. Different output temperatures and flow rates lead to different pressure loads. However, pressure between different arrays of different sizes has to be equalized. Detailed calculations considering the geometrical configuration of each collector are not possible usually for the builder. The installer has to estimate the best values for the valves. In turns, also the dimensions of the pump can only be estimated.

For commercially available Solar Thermal Façades the physical characteristics are not typically available, instead performance parameters calculated by curve fitting are provided by the manufacturers, tested under standard conditions according to EN ISO 9806:2013 [54].

Process barriers

Process barrier are related to the difficulties that can be met from the design to the installation phase. The quantification of human efforts, logistics and engineering is matter of concern since little or no know-how is owned by designers and façade builders.

With regard to modelling and simulation, these new concepts have not been implemented yet in easy-to-use software for designers. Shading is often neglected. One has to simulate the heat transfer from the collector through the wall, particularly for the case of stagnation, and the vapor transfer behavior. The need of simulation tools to predict the energy performance of BIST façades is urgent.

For architects it is very difficult to include solar technologies in the early design stage, when the basic concept of the building is determined. For this reason, simple tools giving synthetic data about the plant size, the performances and a rough impression of the appearance would be needed. Engineers tend to focus on the efficiency of their collectors instead of focusing on easy integration into buildings. In general (also among customers), it is very common to consider the building and solar technologies as separate components. A common language obtained through a simple tool could help to overcome many problems.

Designers might be not aware of the availability of BIST products. On the other side, some customers feared that after several years or at the end of the lifetime, the manufacturers might be not able to offer a suitable replacement for single components of the solar system. It has also to be clear that there are very few producers and many solar thermal collectors' distributors, who do not have neither the capacity nor the possibility to develop new systems.

Munari et al. demonstrated the poor potential for integration of most of the solar collectors available on the Swiss market. Either glazed flat plate, unglazed and evacuated tube systems were considered. It seems that we are still far from seeing solar thermal collectors as architectural elements produced as mass production products [55].

Another hurdle is the absence of building directives for BIST products. The most relevant standards concerning solar thermal technologies are EN 12975 for collectors, EN 12976 for solar thermal systems with non-separable collectors [56], while fundamental reference for façades is the EN 13830, product standard for curtain walling systems [57]. Furundzic et al [58] carried out an interesting study about possible criteria to evaluate the feasibility for Solar Water Heating Systems integration in building refurbishment; they considered climatic and urban planning criteria, characteristics of existing water heating system; architectural criteria. These contain criteria functions which have an own weight factor to be accorded with Investor's preferences. Different solar thermal collectors can be assessed and a "Pareto-optimal" curve is obtained.

<u>Economic barriers</u>

Economic barriers refer to the higher investment cost and the uncertainties related to operation and maintenance costs.

Reliable data about the payback period of future mass products is not available. Mainly because this is closely related to the location, the façade exposure, the energy use. According to the survey carried out by Cappel et al. [53], owners of dwellings claim that solar thermal installations should pay off in a maximum of 10 years (typical warranty for solar thermal collectors) because they fear damage within the expected lifetime of 20 years, while for big investors, payoff periods of 3 to 5 years are attractive. Concerning the manufacturers, they claim that certification is too expensive for uniquely customized collectors. Customized integrated wall systems cannot get the certificate since it is designed for collectors of solar thermal systems according to EN 12975 and EN 12976 only.

Finally, business concepts helping the solar thermal market enhancement are missing. Customer, market offer, revenue and financial models need research. Research can be supportive for the industry.

<u>Social barriers</u>

Social barriers concern the behavior of tenants and public bodies about energy efficiency in buildings.

According to the companies, the strongest social barrier to solar façades is the lack of demand from customers. On the other hand, it should be noted that the companies do not advertise solar thermal façade solutions. Appearance is only the third most important problem for customers, after economic issues and the lack of knowledge. Appropriate and easy contracting or renting models are lacking for solar thermal technologies in general.

The presence of both public and private owners in the same building is another critical situation.

To face all of these issues and to try to overcome them, Research and Development strategies should be fixed and carried on immediately. So, which are the most important R&D priorities that can facilitate the large deployment of solar thermal in multiple market segments?

2.2.2 Research and Development needs and strategies

The European Union aims at a fundamental transformation of its energy system to achieve a reduction of greenhouse gas emissions between 80 to 95% by 2050 compared to the 1990 level [59]. Despite this target, the heat used for space heating, domestic hot water and process heating in new buildings and in the existing housing stock is estimated to amount to approximately 50% of today's heating demand in 2050.

Free solar energy can be used everywhere by everyone, and therefore reduces fuel import dependencies. According to ESTTP [1], solar thermal energy has to face two main challenges. Firstly, solar thermal energy is often still not yet cost-competitive with fossil fuels at today's prices. Especially during last years, natural gas cost decreased unexpectedly. Comparison should take into account the lifetime period of the solar thermal system. Then, competitiveness is strongly dependent on the assumed growth rate of fossil fuel prices. The comparison is biased in favor of fossil fuel costs, as these do not include negative externalities such as the environment, import dependency and other factors. Secondly, there is a mismatch between the supply of solar irradiation and the demand for heating. Seasonal storage, which might be a technical solution, is currently installed in pilot plants, but it is still not affordable.

Solar thermal energy will play a vital role. Up to now, it has only covered a minor share of the heating demand in Europe. Indeed, globally, solar thermal systems cover only 1.2% of space and water heating in the buildings sector [37], although these systems have the greatest potential of all renewable energies for heating and cooling. One of the main reasons is that the technical potential of solar thermal has not yet been developed. So far, public budgets for solar thermal R&D programs have been relatively small and often solely focused on demonstration. In EU countries, the amount of funding that the industrial sector typically invests on R&D does not exceed 5%, possibly ranging between 1% and 3%. European Solar Thermal Technology Platform (ESTTP) experts recognized the need to increase this budget to 10% and this has to be matched by an equal amount from the EU to have a significant contribution to the innovation cycle of solar-thermal technology [47]. Solar thermal has been gravely underfinanced during the 2014-2015 European-commissioned calls. The cumulated budget for solar heating and cooling was 4.4 million € out of 554 million €, which means a share of less than 1 %. A number of calls for proposals was launched between mid-October 2015 and May 2016, and all of them have their deadline before the end of 2016. The program has two main sub-sections, each with a specific budget und sub-topics: *Energy Efficiency (EE)*: 93 million € in 2016 including Heating and cooling, and *Competitive Low-Carbon Energy (LCE)*: 351.54 million € in 2016 including Renewable Energy Technologies. The calls where Solar Thermal technologies might find funding amount to a European contribution of 20 million €, which means a share of 4.5% [60].

The challenges, therefore, are to reduce investment costs for solar thermal systems and, simultaneously, to further increase the solar fraction; as well as developing solar thermal technologies for new applications such as solar assisted district heating, heat and solar cooling for industrial processes. Improved technical and architectural integration of solar collectors into roofs and façades are important undertakings for the sector.

Benefits generated by the increased use of solar thermal collectors:

- *Security of supply: Solar thermal energy will reduce the import of fossil fuels from unstable regions and will reduce the dependency on electricity for heating purposes.*
- *Stable energy prices: Solar thermal will stabilize the energy price for heating, since only the equipment has to be financed when installing the solar thermal system.*
- *Climate protection contribution; New jobs; Technological leadership, if R&D are supported.*

Nowadays in Europe, electricity represents less than 25% of the final energy consumption. Today there is still a tendency to equate energy with electricity. Furthermore, there is a propensity to regard energy production only as a centralized large scale activity, while energy is mostly consumed at the local level and on a small scale. Solar thermal and geothermal applications are predicted to take off fast. Together, they will represent approximately 21% and 45% of the total final energy consumption in 2030 and 2050 respectively. According to ESTTP, by 2030 renewable heating and cooling technologies could supply over half the heat used in Europe [1].

Technological achievements to promote the deployment of the solar market are necessary. This means [47]:

- *Developing storage systems that accumulate enough heat to meet the requirements of a house for at least a week or better a month;*
- *Developing appropriate system designs and control strategies in order to achieve the maximum benefit from new storage technologies;*
- *Boosting the combination of solar thermal systems with other technologies into hybrid systems (combined photovoltaic-thermal systems);*
- *Developing new polymeric materials and glasses with improved optical properties for collectors;*
- *Improving heat transfer materials for temperatures up to 250°C (medium temperature collectors).*

The already mentioned *Solar Active House* concept is very promising, since it meets the 'Nearly-Zero Energy Building' requirements that will become compulsory in the EU in 2020. The R&D priorities aim to reduce costs, increase the solar fraction per building and to improve the reliability of solar thermal systems. To encourage innovation in the marketplace, new developments in terms of R&D need to be complemented by standards and measures for quality assurance. This requires developments in standardization, testing and certification to facilitate a sustainable market development and improve trust among consumers.

People from industry and the building sector must be trained to understand and be able to design and install solar heating and cooling systems and integrate them into HVAC and building systems. Moreover, several socio-economic aspects need to be addressed by specific research projects, including the lack of awareness of the solar heating and cooling potential, difficult access to finance, lack of adequate business models and low priority of energy issues compared with other costs.

R&D should not only address the development of products for European, but also for the Mediterranean, Asian and other international markets. A wide exchange program for master and PhD students within research institutes in all member states should create the basis for a European-wide network of scientists working in this field.

How quickly could the cost reduction materialize if sufficient R&D support is given and the market develops well?

From 1995 to 2010, production costs were cut by nearly 50%, with a learning factor of 23%. This means that by doubling the total sold collector area, production costs were cut by 23%.

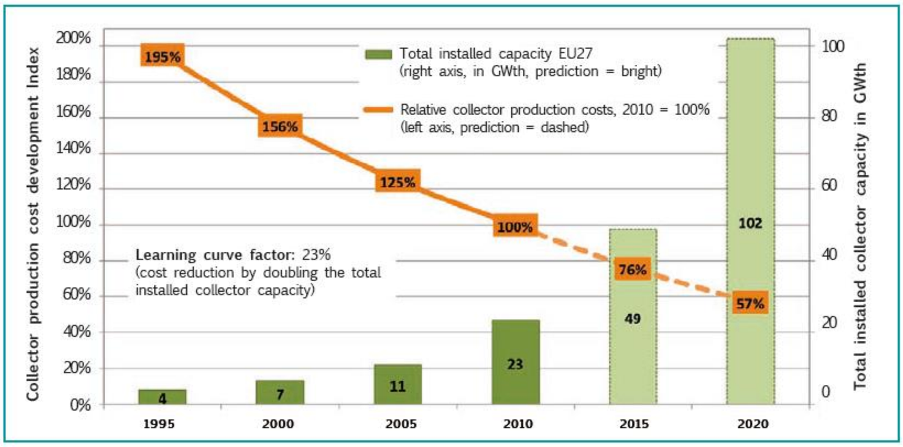


Figure 23 - Collector production costs development for high-efficient flat plate collector panel of about 2.2 to 2.5 m² gross collector area manufactured in Europe [1]

Solar thermal heat costs are mainly determined by the upfront investment consisting of: the solar collector, storage, plumbing, pumps, controller as well as other components, and the installation costs. The average turn-key cost of a solar-thermal system today is about 1100 €/kW_{th} for pumped systems in central and northern Europe, and, 600 €/kW_{th} for thermosiphon systems, which are used typically in southern Europe. Experts from the technology platform claim that if the installed solar-thermal capacity reaches 200 GW in 2030, system costs for small scale forced circulation units installed in central Europe will reach €400/KW_{th} [47].

Depending on the size of the system, costs for the collector area represent typically between 20% and 40% of the whole system. In some countries, the installation costs of small domestic hot water systems may reach 50% of the investment. The investment depends on the type and size of system used, varying from below 300 €/kW_{th} for large-scale district heating systems up to 1700 €/kW_{th} for a combi-system. A new Task, within the IEA program, dealing with *Price Reduction of Solar Thermal Systems,* started in 2015 (http://task54.iea-shc.org/); the aim is to investigate ways to make solar thermal more attractive by improved marketing and consumer-oriented design.

2.3 Requirements and standards for solar façade systems

What does really make the difference between a solar thermal façade and a traditional façade with applied solar technologies? Even if solar thermal façade solutions already exist (as shown in the last paragraph), standards to build these systems have not been conceived yet. In this chapter, standards for solar thermal collectors are recalled to understand if they can find applicability for solar thermal façades or if they can inspire a new product standard. In the end, a list of requirements that solar façades should satisfy is projected.

According to European Technology Platform [1], schemes for product certification will be available, covering not only the solar thermal system itself but also the system delivering the auxiliary energy. The certification schemes will be implemented and accepted globally or at least Europe-wide.

On the ESTIF's website (http://www.estif.org/solarkeymarknew/consumer/european-standards), a list of standards applicable for solar thermal technologies is reported. To get an overall description of the elements included in solar thermal systems, EN ISO 9488 [61] is good reference containing the vocabulary used in the Solar Energy field. The most relevant European standards are the standard series EN 12975 for to solar thermal collectors [56], EN 12976 for factory-made systems [62] and EN 12977 for to custom-built systems [63].

EN 12975 specifies requirements on durability (including mechanical strength), reliability and safety for liquid heating solar collectors. It also includes provisions for evaluation of conformity to these requirements. Among the requirements to be tested: high temperature resistance; exposure; external thermal shock; internal thermal shock; rain penetration; impact resistance; mechanical load; thermal performance.

EN 12976 is the European Standard for factory-made solar thermal systems. Part 1 specifies general requirements and part 2 is about test methods.

EN 12977 concerns custom-built systems. This standard is composed of five parts. Part 1 describes general requirements for solar water heaters and combi-systems; Part 2 specifies test methods for solar water heaters and combi-systems; Part 3 is about performance test methods for solar water heater stores; Part 4 defines performance test methods for solar combi-systems and Part 5 focuses on performance test methods for control equipment.

Quality should be assured by certification schemes for products, systems, but also planning and installation processes. Over 90% of collectors sold in Europe are labelled with *Solar Keymark* (voluntary third-party certification mark for solar thermal products based on the European standards), since it is required in most of the European countries to benefit from incentives. Quality assurance measures based on the certification of products, installations and services, as well as the possibility to determine and assess the functionality and performance of the system in an easy and cost-effective way, can increase the consumer confidence in solar thermal products (STCs, Factory made STSs, Complete systems and system components). The certification of products, systems and services is crucial to gain high consumer confidence. R&D and further activities are required to widen the scope of the successful *Solar Keymark* certification scheme to other system categories, such as combined solar thermal and heat pump systems [1].

Applying or integrating solar thermal collectors on façade is something that lie outside the certification of roof-mounted installations. STCs manufacturers might fear that the quality they can offer is no more the same, once their products are integrated into façade.

According to ESTIF [64], *CE marking* of solar collectors related to the Construction Product Regulation (CPR) is under preparation and will cover:

- *Mechanical resistance to climatic loads (wind, snow, …)*
- *Fire safety (e.g. initiation, reaction to fire, risk to adjacent elements)*
- *Weather tightness (when relevant - i.e. for roof or façade integration)*

Another constraint is related to the pressure and the volume of the fluid content; indeed, solar thermal collectors are also subject to *CE marking* related to EU pressure equipment directive (PED).

The mentioned requirements for solar thermal collectors and solar thermal systems should be also applied to BIST façade products. Many needs are shared with façade systems, so *CE marking* for Solar Thermal Façade Systems should be pursued.

The integration of solar thermal collectors into façade can be an interesting application giving to the envelope both a new design and new functions. Matuska et al [65] stated that application of façade solar collectors on façade increases indoor temperature by no more than 1 °C when sufficient insulation layer is present. Zhang et al. [28] compared different solar thermal technologies suited for façade integration. They recommend the installation of evacuated tubes as balcony balustrade (Figure 24) since the tubes are standardized products with easy joining and the number of paralleled tubes can be flexible according to the energy demand or construction size. Related to glazed and unglazed flat plate collectors, evacuated tubes have a higher energy efficiency and operate at higher temperatures (in the range of 80-180 °C), favorable to produce also solar cooling. The fragility of vacuum tube collectors is a weak point during the transportation. Within the FP7 *Cost-Effective* project [4], they came up with the realization of different façade concepts integrating active technologies, including the integration of air-heating vacuum collectors within the cavity of double skin façades (DSF) to gain energy and shade the indoor environment from the sun. Glass tubes are also protected. Potential failures linked to mass transport were not reported. Main stressed disadvantages are the increased risk of glass breakage due to high thermal loads within the façade cavity and the increased cost for cleaning and maintenance compared to a double skin façade without any system installed in the cavity.

Figure 24 - Evacuated tube collectors integrated into façade [Schott-Rohrglas]

Table 3 is structured to summarize the main requirements at façade, building and urban scale, trying to give emphasis to the active façade related aspects.

Table 3 - Façade, whole building and urban context related requirements

	Basic Requirements	***What needs to be evaluated***
FAÇADE REQUIREMENTS	Energy economy and heat retention/hygiene, health and environment	U values for opaque and transparent components
		Heat losses: thermal bridges localization and quantification
		Water vapour transfer: inwards and/or outwards (permeability) rate and potential risk of condensation
		Solar control: fixed and movable shadings, effect of the final wall thickness, transparen-to- opaque ratio, light transmission properties of transparent components
		Air tightness
		Safety in use: potential damages during installation and operation
		Release of dangerous substances
	Functionality	Safety: burglary protection and no access to energy system from outside
		Permeability and drainage: water and air tightness and water drainage
		Maintenance: accessibility of the modules from indoor environment; inspection recurrence
	Mechanical resistance and stability	Façade static and dynamic: mechanical behaviour under services and extreme working conditions
		Wind resistance
		Impact resistance
		Resistance to own dead load
	Energy production over time	Functional integration among façade modules
		Liquid (energy carrier) durability
		Pressure drops
	Environmental impacts and durability	Façade components durability: resistance to high temperatures
		LCA: re-use of components at the end of life
	Protection against noise	Critical nodes detection
		Envelope soundproof: façade materials and glazing typology
		Noise from circulating water/air system
	Safety in case of fire	Resistance to fire: components and material choice
		Material's reaction to fire: dropping and smoke paths and control
		Fire compartments: façade modules junctions
		Solar thermal
WHOLE BUILDING REQUIREMENTS INFLUENCED BY THE FAÇADE FEATURES	Energy demand, energy consumption and production	Energy demand reduction: heating and DHW demand decrease
		Energy demand load: cooling demand increase
		Nearly Zero Energy Building: incidence of the system in achieving the target
		Indoor comfort: air and surface temperatures, indoor relative humidity, internal air velocity, visual discomfort
	Hygiene, health and environment	Hygienic air changes
	Mechanical resistance and stability	Envelope safety in use: anchoring system
		Seismic behaviour: influence of façade on building behaviour
	Aesthetic and Functionality	Façade composition: impact of the external layer (color and shape) on building features
		Energy system size: reduction of the centralized energy system
		Hydraulic layout control: connection from façade to centralized energy system
URBAN CONTEXT REQUIREMENTS	Energy demand, energy consumption and production	Energy system efficiency: possibility to create a district heating grid
		Nearly Zero Energy balance at district level: how façade contributes?
	Location constraints	Safety in use: possibility to use cranes for installation
		Site accessibility
	Aesthetic and Functionality	Building regulations compliance: impact of the new façade at district level

2.4 Solar thermal façade performance indicators

Can standard façade performance indicators be applied to building integrated solar thermal façades? At first blush, the answer is no since the building physics implemented into the façade is different. The usual indicators, visible to the investor, are the thermal transmittance and the solar heat gain coefficient, which are actually two inputs in the design of a façade. They do not give any information about the influence on energy consumptions, thermal and visual comfort and costs.

Starting from the requirements for curtain wall façades, listed in the product standard EN 13830, performance indicators for solar thermal façades are proposed.

Performances of complex façade systems

Solar thermal façade systems are construction products and, as such, they contribute in making the building compliant to the basic requirements listed in the European Regulation 305/2011 for construction works [66]. Indeed, according to this regulation construction works have to be carried on in a way such as to fulfill the following requirements:

1	*Mechanical resistance and stability*	▪ No collapse of the whole or part of the work. ▪ No damage due to deformation of the load-bearing construction. ▪ Proportion between damage and original cause.
2	*Safety in case of fire*	▪ Generation and spread of fire and smoke are limited. ▪ Limited spread of fire to neighboring. ▪ Safety of rescue teams.
3	*Hygiene, health and the environment*	▪ Construction works should not be a threat to the hygiene or health and safety of workers, occupants or neighbors. ▪ No exceedingly high impact, over their entire life cycle, on the environmental quality or on the climate during their construction, use and demolition.
4	*Safety and accessibility in use*	▪ Construction works should not present unacceptable risks of accidents or damage in service or in operation such as slipping, falling, collision, burns, electrocution and injury from explosion and burglaries. ▪ Construction works must be designed and built taking into consideration accessibility and use for disabled persons.
5	*Protection against noise*	▪ Noise perceived by the occupants or people nearby has to be kept to a level that will not threaten their health and will allow them to sleep, rest and work in satisfactory conditions.
6	*Energy economy and heat retention*	▪ Heating, cooling, lighting and ventilation installations must be designed and built in such a way that the amount of energy they require in use shall be low. ▪ Energy efficient construction works, using as little energy as possible during the construction and dismantling.
7	*Sustainable use of natural resources*	▪ Reuse or recyclability of materials and parts after demolition. ▪ Durability of construction works. ▪ Environmentally compatible raw and secondary materials.

Construction products contribute to fulfill these requirements at building scale through their essential characteristics, which in turn are linked to specific performance indicators. For example, metrics for curtain wall façades are referenced by the product standard EN 13830. This standard is a good starting point to set metrics suited for active façade systems. Then, metrics have to be connected to specific reference standards (international, national or local regulations/norms) specifying the calculation and/or the test method. For example *water tightness* is an essential characteristic for curtain wall systems listed in the EN 13830 [57]; this is a metric as well to be determined through both calculation and test according the norm EN 12208 [67]. The metric helps the building to meet the requirement *Safety and accessibility in use*. Stagnation temperature control might be another key factor.

Solar thermal collectors usually are mere elements applied on a roof or on the ground by means of a substructure. These products have to be harmless and contribute to reduce the energy consumption of a building, but the current characterization of STCs does not conceive impact resistance, sound reduction index or other features typical of façade components. It is just determined by the analysis of the optical and thermal properties of the components or by the thermal performance testing of the complete collector under controlled conditions. Characterization is essential to provide information that can help [68]:

- *Manufacturers to optimize the design of collectors*
- *Designers of solar heating systems to select components and to optimize system performance for specific applications*
- *Consumers to compare the performance and cost-effectiveness of competing products*

The performance indicators used to assess standard STCs are:

Heat removal factor

This is the rate of extraction of solar energy by the heat transfer fluid. Detailed heat transfer models have been developed in the past to describe both the transient and the steady-state performance of different solar collector types. Several years ago, solar collector models were developed based on steady-state performance, neglecting the energy storage in the collector. This metric is linked to the flow rate; the higher the flow rate, the higher the heat removal factor until a maximum flow rate.

Optical efficiency (zero loss efficiency, η0)

It represents the collector's thermal efficiency with no consideration of the losses by convection and radiation. In other terms, when the absorber temperature is equal to the ambient temperature.

$$\eta_o = \tau_c \cdot \alpha$$

Where τ_c is the transmittance of the front glass and α is absorptance of the absorber.

Solar thermal efficiency (η_{th})

Under the steady-state conditions, the useful heat delivered by a solar thermal collector is equal to the energy absorbed by the heat transfer fluid minus the direct or indirect heat losses from the surface to the surroundings.

$$\eta_{th} = \frac{Q_U}{G_T \cdot A_C} = F_\alpha \cdot \tau \cdot \alpha - F_R \cdot U_L \cdot \frac{T_i - T_\alpha}{G_T}$$

Solar fraction (f)

It is defined as the ratio of the primary energy saving that a STC can achieve to the overall energy demand.

System efficiency (SE)

This indicator gives the ratio of solar heat yield to the global solar irradiance on the absorber surface with respect to a given period of time. This parameter is dependent on the solar fraction. If f is amplified by increasing the collector area, the SE will decrease. This means that the cost per kWh energy generation is high.

Environmental sustainability

It is related to the materials and components. LCA and Environmental impact techniques are useful tools for the evaluation of the environmental profile of a solar installation. Life Cycle Inventory for BIST systems is still difficult to find, since producers rarely disseminate this information. The number of system components is crucial since more complicated systems are expected to have higher initial impact, during the manufacturing phase. New concepts promoting alternative materials to reduce the embodied energy have been developing.

Energy Pay Back Time (EPBT)

A solar system is proved to be more environmentally friendly on a longer term basis, even if a critical factor to assess this indicator is the electricity/fuel mix adopted. Recycling is another important factor. By adopting materials that can be recycled like aluminum, copper and steel, a reduction in the environmental impact can be achieved.

Normalized solar heat costs

The economic performance of a solar system can be described with the help of the *normalized solar heat costs*, which is the cost per kilowatt-hour. This metric considers both the investment costs and operating costs (power for the circulating pump and maintenance costs), calculated with the energy yield during the service life.

Besides proper components' performances, new calculation methods taking into account the effect of the integration of components into façade (building physics) are needed. Energy uses, embodied energy and comfort are only a few of these performances. In Europe, no standard concerning BIST systems and related metrics are present. On the other hand, a new regulation in the field of Building Integrated Photovoltaic (BIPV) has been issued recently (*EN 50583-1:2016 - Photovoltaics in buildings. BIPV modules)* [69].

Several indicators should characterize a solar thermal façade as those related to a standard unitized system like thermal transmittance for the Curtain Wall (Ucw), sealants durability, fire heat release rate, water tightness and many others. Obviously, these parameters should indicate the deviation of performance due to an active system integrated into the façade. Thermal transmittance, solar heat gain coefficient, visible transmittance and other values usually associated to building envelope elements like glazing systems, frames or materials do not express the real performance of the solution. Performance indicators like daylight autonomy, energy consumptions and thermal comfort (PMV) depend on the use of the building, the climate conditions and other factors, besides proper envelope systems features.

Unlike non-integrated roof installations, heat losses occurring into solar thermal façades are not easily quantifiable. The façade case study, which is explained in chapter 3, includes both pipes and a water tank, which have not an ambient air temperature as boundary condition, but a temperature that results from a mutual interaction of fluxes occurring within the façade thickness. Estimations of heat losses of pipes insulated with mineral wool can achieve almost 7 W/m if a temperature difference of 30°C is considered. If the solar circuit length amounts to 20 m and works for 2000 hours per year, heat losses amount to 280 kWh/y. The solar energy yield of a 5 m² glazed flat plate collector surface area is around 2000 kWh/y (5 m² x 1000 kWh/m²y x 0.40). Heat losses would be 14% of the annual yield. A factor 3 can be reached if pipes are not insulated [70]. Concerning the heat losses from the water storage, these increase in proportion to its upper surface area and the temperature difference between the store and the surrounding environment. The façade case study has a storage well insulated on each side of the system, and the upper horizontal area is small compared to the lateral ones.

O'Hegarty et al. [20] assessed four types of solar thermal collectors integrated in different ways by comparing the instantaneous efficiency curves. In accordance with ISO 9806, the term (Tf,i - Ta) was replaced in with (Tf,m - Ta), where Tf,m is the mean of the inlet and outlet temperatures. The performance of market available evacuated tube collectors and flat plate collectors based STFs are simulated using the equation

$$\eta_i = \eta_o - a_1 \cdot \left(\frac{T_{f,m} - T_a}{G}\right) - a_2 \cdot G \cdot \left(\frac{T_{f,m} - T_a}{G}\right)^2$$

For unglazed collectors (UC), the absence of a glass cover results in a linear form of the efficiency equation, given by

$$\eta_i = \eta_o \cdot (1 - u \cdot b_u) -\cdot (b_1 + u \cdot b_2) \cdot \left(\frac{T_{f,m} - T_a}{G}\right)$$

where η_0, b_1, b_2 and b_u are performance parameters for the UC. The different form is due to the absence of a cover, hence greater heat loss. Figure 25 shows the obtained curves together with a reference case that is a typical Flat Plate Collector (FPC).

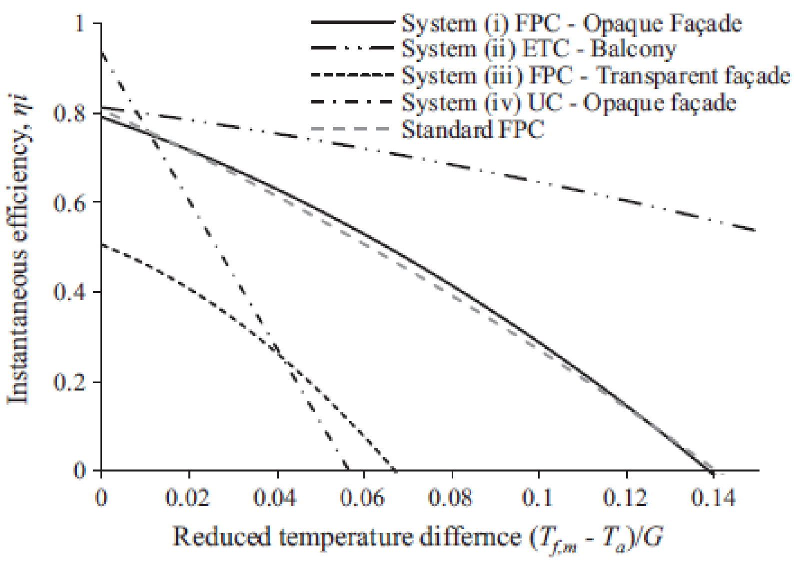


Figure 25 - Theoretical efficiency for four Solar Thermal Façade systems [20]

Within the COST action 1403 about Adaptive Façades, performance indicators for complex façade systems like double skins, solar air walls, and chromic glasses are being defined. EURAC'S

Institute for Renewable Energy is involved [71]. Some metrics like thermal transmittance (U-value) and solar factor (g-value) are not new, but calculation methods considering the dynamic behavior of both opaque and transparent façade components are under investigation to obtain equivalent values.

Performance indicators requiring investigation and calculation methods are:

Equivalent façade thermal transmittance, defining the dynamic thermal insulation capacity of an active façade

Equivalent g-value, showing the solar heat gain variability

Air cavity (STC rear side) temperature gradient, as expression of the thermal energy generation and pre-heating efficiency of air-based solar façades

Heat removal efficiency, defining the capacity of double skin façades or solar air walls of reducing the cooling load during summer

Water storage efficiency, intended as the capacity of the water storage integrated in a façade system considering heat losses and resistance of façade components to high temperatures

These performance indicators could be adopted to characterize Solar Thermal Façades. The presence or not of an air-gap on the rear side of the collector affects either the thermal transmittance, the heat removal rate and the flux transmitted through the wall construction. The efficiency of components integrated into façade, like a storage system, are mutually influenced. The quantification of these effects is possible only through test measurements and validated models that are still absent in energy simulation tools like Trnsys and EnergyPlus.

The second chapter went through the analysis of existing solar thermal technologies, their readiness as façade integral elements and solar thermal envelope systems already brought to the market. For single technologies and components of solar thermal systems, advantages and limitations can be detected, but different is the scenario when solar thermal façades are examined. Indeed, just a few data in terms of costs, commercialization, number of applications and maintenance needs were found. The presence of products on the market and the uncertainties linked to single components create a misleading situation, where solar thermal façades seem to have acquired a reputation but still not sufficient to be considered potential competitive design solutions. Main challenges remain the reduction of investment costs for solar thermal systems and, simultaneously, the increase of the solar fraction; as well as the better exploitation of the produced energy during summer, thinking about new applications such as solar assisted district heating connecting buildings with different use (residential and industrial). Improved technical and architectural integration of solar collectors into roofs and façades are also important undertakings for the sector.

Finally, as stated by the European solar think tank, research funding, incentives and subsidy mechanisms are necessary to encourage the opening of a new branch for the solar thermal business. Lesson learned from financial support schemes that did not w ork in the right way during last years should be taken to promote new business approaches.

Chapter 3

3 Technology analysis and economics of a solar thermal façade

Main objective of this chapter is the comprehension of the risks and the costs associated to the solar thermal façade used as case study. The analysis goes through single components issues, façade element features and design process inconvenient. Two façade builders who are based in South Tyrol (Italy) were interviewed to understand the general interest around new active façade configurations. Questions and answers are reported. The collected information represent the grounds to build the tool illustrated in chapter 5, aimed to ease the communication between involved parts and to support the assessment of solar façades in the early design stage.

Keywords: technology analysis; maintenance; façade cost analysis

3.1 The technology case study

Within this research program, no new active technologies were developed or studied. Indeed, the research is aimed to enhance the market introduction of solar technologies by means of an instrument implementing disciplines: from technology and performances to costs and durability.

A unitized façade system made with aluminium profiles and glass way was used as case study. The façade integrates several active components aimed to build a hydraulic circuit within the opaque façade thickness. As most of the curtain wall systems in Europe, the façade has been conceived for office buildings. The envelope system has been developed within a small project co-funded by the province of Bolzano (Italy); two main actors have carried on the activities: the *Institute for Renewable Energy of EURAC Research* and *Stahlbau Pichler*. The first company is an applied research center dealing with renewable energies implementation at different scales: urban level, district area and building scale. The second company is renowned name in the field of façades for buildings. Both the companies are located in Bolzano, in the region of South Tyrol, Italy.

Since the object used as case study of this dissertation is an industrial product, the author has interviewed manufacturers of the façade sector to test the waters. Aim of the questions addressed to the interviewees was to investigate the interest on active façades of those who produce the building envelope to understand if they have already faced the active components integration. Construction companies have to match the desire of the designers within fast processes coming to conclusions in a short time. The general question is how to match the production of complex façade systems with short construction durations. What would be needed to start a production line including also active façades, besides the market demand?

Five façade manufacturers dealing with aluminum-glass curtain walls were selected and contacted to schedule interviews in person or by call. The questionnaire was sent to all of the companies but only two of them have shown up. Both the façade companies are well-known at international level and they are based in South Tyrol (Italy). Observations and deductions coming from the interviews have been reported in this chapter and the final paragraph is a summary of the answers obtained.

Dealing with innovation means necessarily going in the opposite direction or against someone else who does not want that solution/idea to be spread around because it is disadvantageous for his/her own business or simply because it is not interesting to him/her. The experience in *Sun-RISE* Project has given to me the opportunity to see how hard is facing innovation. Innovation never comes out from a single person. A partnership is always needed and a continuous iteration process to share ideas is unavoidable. In this case the institutions/figures involved have been:

- *Eurac as coordinator of the project, developer of the idea and main contributor for the performance assessment (energy performance studies through simulations and test, economics, technology analysis and façade layout) and collector of information*
- *Stahlbau Pichler: italian façade manufacturer dealing with metal-glass façades, who has developed execution façade details and has built the prototype tested at Eurac laboratory IN-TENT*
- *Several system suppliers for components to be integrated into the façade (Öko-Tech, Austrian company producing solar thermal collectors; Hatek, Italian company producing radiant panel systems; Pink, Austrian company building water storage systems)*

The façade energy concept conceives the production, storage and distribution through the integration of different technologies in the opaque part of the façade. A solar thermal flat plate collector is installed as external layer. The collector has a 20 mm air gap to guarantee the removal of the eventual moisture deposit. An insulated water tank storage is located behind the solar thermal collector. The façade insulation layer (mineral wool), where pipes to connect components are located, divides the storage tank from a radiant panel installed as inner layer of the façade construction, as represented in Figure 26. This energy distribution system is supposed to substitute traditional fan-coil units, gaining space inside the building.

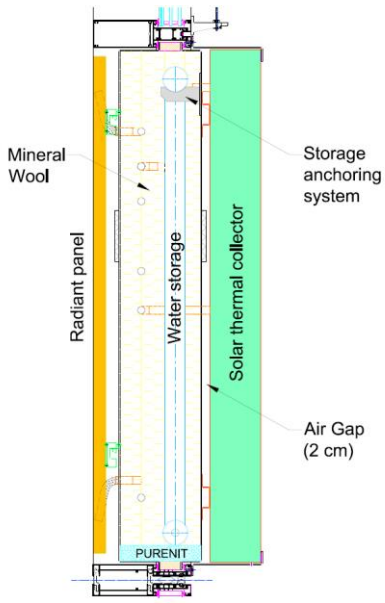


Figure 26 –Façade case study_Vertical section and construction layer

The façade is a multifunctional system providing solar heating when sun is available and heating needed, solar DHW/storage, and space heating and cooling through the radiant system thanks to the auxiliary energy centralized system. Operation modes are showed hereinafter.

Concerning the dimensions of the façade module, many times it has been discussed if façade had to fit the solar collector sizes or vice versa. Both solutions actually should be analyzed in order to understand the flexibility of the system. Hypothesis about the application on a building have been advanced: office buildings with regular shape could be suitable for this product. Where the BIST façade is not used, the envelope can still be active but integrating only the distributive part. BIST façade modules should be installed according to designer choices, thermal needs during the day and the year, and control strategies; one problem is that heating load is usually low for this kind of buildings, but heating system is unavoidable. Façade specifications have to get along with the climate. Window to Wall Ratio (WWR), glazing type, insulation thickness, percentage of active area are only a few of the input to be assessed for a façade system. With complex façade systems like this other parameters become essential.

A 3D sketch of the façade system is showed in Figure 27. The possible appearance of the modular system application is displayed to the right.

Figure 27 – 3D sketch of the unitized façade concept (left) (source: EURAC) and possible application result (right) (source: Metal Technology)

The main reason why this solar thermal façade was chosen as case study regards the representativeness of complex façade systems where water is expected to circulate and many components have to be inspected over time. Hence the design becomes extremely important and finding a way to communicate the concept becomes more motivating. The façade case study is reputed quite significant and facing other solar façade solutions should be easier from the technology point of view. The author believes that, showing the possibility of a complex façade system of being comparable with standard solutions can help enhancing the market of new façade concepts. Indeed, thermal technologies are suffering the market boost more than others are. Other case studies were observed and reported in this work, but no one was analyzed like the façade subject of study.

New façade systems should take advantage of existing active technologies and components. The development of new components could bring to not successful solutions. Only if none of the existing technologies is suited for the specific functionality to be integrated into the façade, it makes sense spending time in developing something new. Building-integrated services like mechanical ventilation might find place into the façade or close to it (like in the slab just below the façade) as it was demonstrated with some products, so flexibility in this sense should be considered.

3.1.1 Components

To be competitive on the market, an active façade should integrate components, which substitute usual technologies installed inside the building, or at least reduce the size of installations (radiators, fancoil units, storage tanks) since the envelope is contributing to produce and distribute thermal energy. Adding new active components to a usual building energy system is equal to fail.

The European Standard EN 13830 does not give any specification concerning the integration of components like STCs or PV panels. It might be reasonable asking themselves if there are constraints in fixing elements/components in front of the façade opaque part. No limitations are prescribed in terms of thickness of the façade. The Product Standard speaks about façades as curtain walling kits.

The façade case study is made of six main components: (i) aluminum frame; (ii) glazing system; (iii) solar thermal collector; (iv) radiant system; (v) water storage; (vi) hydraulic control box/connections. The first two items are basic components of every curtain wall system, while the other four elements are the special feature of this active façade concept.

Solar Thermal Collector (STC)

The technology used to build the prototype is a Glazed Flat Plate Collector. A standard product was used to avoid high cost in this preliminary stage. These led to the façade system (aluminum frame and total width) adapting to the solar thermal collector. The STC size is 1m (height) x 2m (width). However, fitting the usual façade size would mean using a 1.5m wide collector.

The solar collector supplier highlighted the importance to have a ventilated layer behind the solar absorber and the need of a rear-side insulation layer to reduce heat losses and to guarantee the removal of potential moisture deposit. Issues to be faced were the steam transportation from inside and the potential leaks in connections and barriers that can be dangerous. Since a non-standard product is used, it was necessary understanding the need for *Solar Keymark*. How *Solar Keymark* certificate is affected by variations in terms of absence of insulation, insulation thickness and other aspects is something to be faced. *Solar Keymark* costs around 15,000 €, but it is not thought for special applications like the mentioned case study.

Radiant System

Radiant panels made up of external metal sheet, copper tubes and thin insulation material between pipes, are used as wall radiant system. External surface is the façade finishing as well, hence aesthetic is essential and potential splits should be well designed. Depending on the use of the building (internal loads) and solar heat gains, the radiant panel power was calculated. Since this system is supposed to substitute a traditional air convective system, the radiant surface has to cover the energy demand and create a comfortable indoor environment.

According to the company dealing with water-based radiant systems, depending on the supply water temperature and the indoor air temperature, the energy yield varies between 135 and 203 W/m² for the heating mode and is in the range of 98 and 125 W/m² for the cooling mode. Mass flow rate varies between 35 and 55 kg/h/m², depending on heating or cooling mode. The radiant system costs between 200 and 230 €/m² depending on the presence of a perforated or continuous front metal sheet, the rear-side metal sheet, the hook system.

The radiant panel is fixed through hooks to the metal shell inside the façade opaque portion. Flexible tubes connect the panel to the water storage. This way, the radiant system can be easily moved for maintenance or visual inspections.

<u>Water Storage</u>

An element made of vertical circular pipes welded at the extremes to two horizontal tubes (headers) was used as water storage for the façade element. The tank is a carbon steel-based element insulated with mineral wool. The tube at the bottom works as heat exchanger. The system is loaded from the bottom. The capacity is 60 l. Usually 50 l/m² of solar collector area is the volume associated to a solar thermal system. Hence, the water tank is underestimated considering the solar thermal collector surface area is 2 m². Li et al. [72] developed a Building Integrated Curtain Wall (BICW) façade system and considered a water-storage to collector-area ratio of 50 l/m². The circulation pump provided a forced circulation of water through the collectors at a fixed mass flow rate of 0.12 kg/s. The author of the thesis stresses the point that this component has been produced for the specific prototype. However, other solutions could be implemented like sort of boxes with polymeric materials.

About the insulation of the system, two solutions are available: one is using PU foam and the other is wrapping up the whole radiator with VIP. VIP assures 30% better performance in terms of heat losses reduction but is expensive according to the producer. A 6 bar pressure was considered. Research about an optimized technology or suited standard solutions is necessary to find a cost-effective component.

The storage is placed inside a metal shell, containing also distribution pipes, the insulation material and a control box with valves and circulation pump.

<u>Hydraulic control box and connections</u>

Moving solar thermal collectors in façade implies moving pipes on a vertical plane, differently from what usually happens with hydraulic systems with pipes running horizontally.

S-Solar developed and started to commercialize a BIST product to be mounted as a glazing system [73]. Behind the glass is an integrated energy unit with absorber, thermal insulation and pipe fittings. Hydraulic connections can be vertical or horizontal (Figure 28).

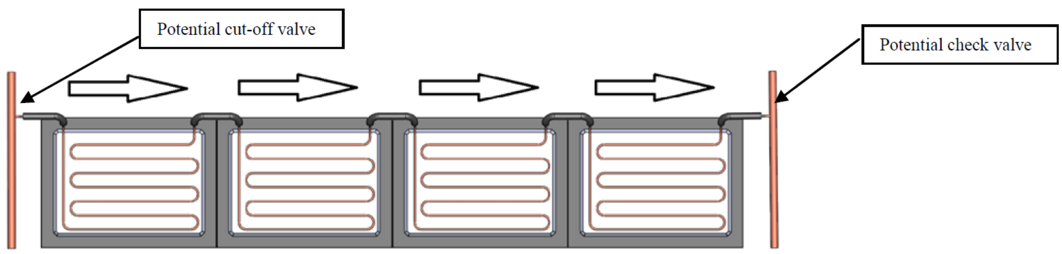


Figure 28 – Horizontal technical fluid connection - Source: PRISMA solar collector by S Solar [73]

Thanks to their experience with horizontal installations, they recommend the solar collector's coils should be horizontal and that the flow is from below and upwards in the meander section to achieve as simple aeration as possible. It is best to install the cut off valve before the first solar collector in the group, and a check valve after the last solar collector in the group. The check valve must be able to cope with a temperature of 230 °C and maintain a pressure classification of 10 bar at this temperature.

Within the façade case study context, hydraulic connections pertain to both the single façade module and two façade modules when connected. The single façade module has pipes to link the solar thermal collector to the water storage, and other pipes to supply water directly from the storage system to the radiant panel. Pipes running into the façade connect more façade modules from the hydronic point of view. As showed in Figure 29, several pipes have to pass from a module to the adjacent one to allow the fluid to run completely the solar loop. The module to the right has the box including all the control components (pump, valves, expansion vessel). The control box is accessible through a small door, which can be opened once the radiant panel is moved from its position.

This thesis does not go into the detail of these aspects, but a significant work was carried out to understand where to install tubes and eventually to get a feasible façade layout. Once the tubes are installed into the façade and insulated, there is no chance (and need) to work on them, except for the pipes junctions positioned in line with the façade mullions. The most important façade section where there might be need of maintenance during the building operation is the control box (with the valves and the pump). A small door, located behind the radiant panel, is obtained in continuity with the metal sheet of the insulation layer to access the control box (far right in Figure 29). Every solar thermal series of façade, which might correspond to a number of façade modules covering the width of an office room should be provided with a control box located only in the first module of the series.

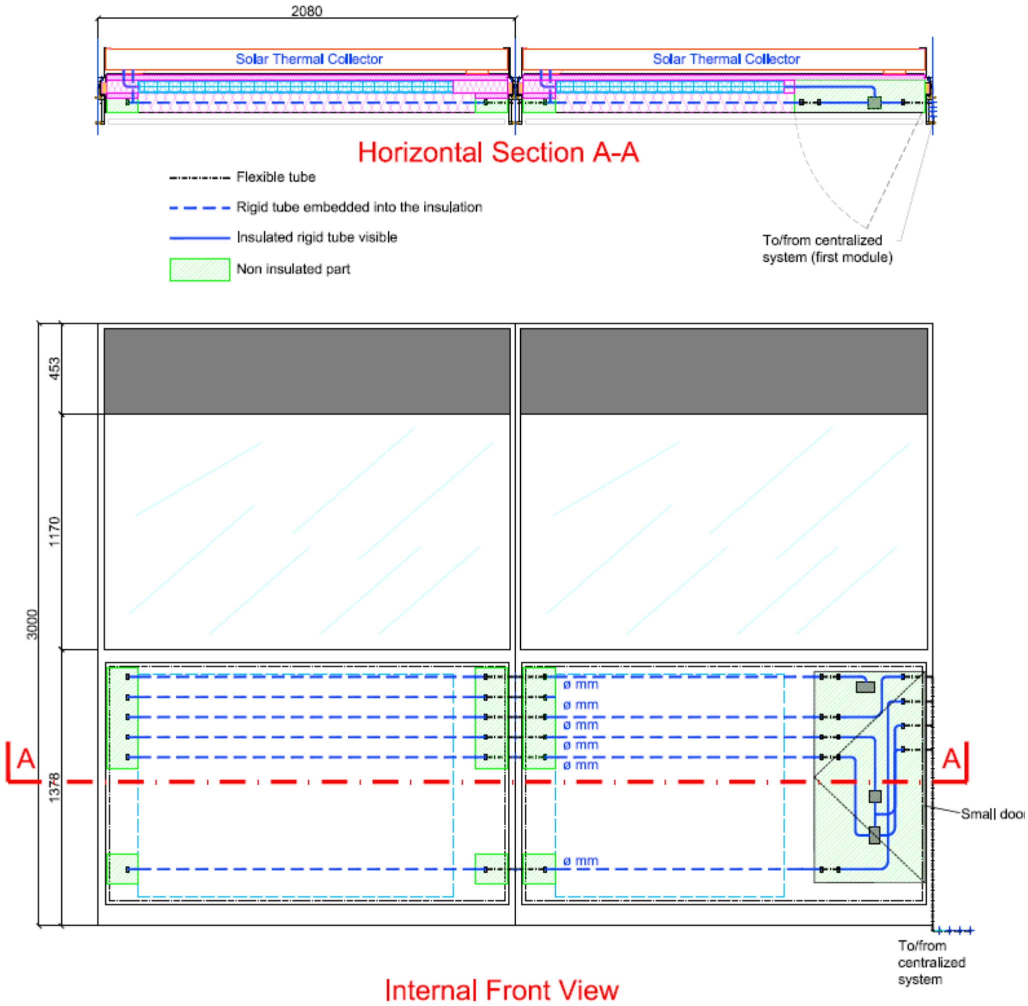


Figure 29 – Façade case study_Front view from inside and horizontal section

Since the hydraulic façade layout is not the focus of this thesis, no technical details about the components of the solar façade circuit (pumps, valves, probes) are reported. On the other hand, some issues concerning the passage of pipes between façade modules, and how these have been solved, are stated.

3.1.2 Concept description

Li et al. [72] characterized their BICW façade by switching on pumps when the temperature difference between the bottom of the water tank and the outlet of the collector exceeded 10°C, and they were switched off when the difference was less than 4°C. For the heating supply circulation, the hot water was pumped to fancoils to supply heating in winter. In the heating supply circulation, the pump was kept running when the outlet temperature exceeded 50°C and the temperature difference of the inlet-outlet circulation exceeded 5°C. The pump stopped pumping when the temperature difference was less than 3°C.

As mentioned, the façade case study has more functionalities, making the control strategy more complex. Here follow a description of all the operative modes, depending on boundary conditions.

- *Solar Harvesting/Storage charge*

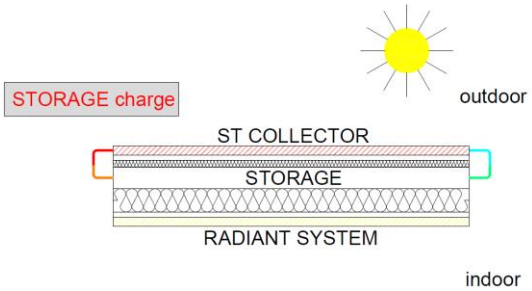


Figure 30 – Façade case study_Solar Harvesting schematic layout

The loop involves the solar thermal collector and storage tank of each façade module connected in series. The water goes from the hydraulic box to the farther STC (C1), and then it goes into the farther storage (S1). From S1, the water goes to the adjacent solar thermal collector (C2), then it goes to S2, then C3 and finally it passes through the last storage (S3). At this point water goes back to the hydraulic box. This operation mode is needed to load the storage tanks before delivering the heat to cover the heating demand or the DHW. As long as the temperature of the water coming from S3 is lower than the Radiant system supply temperature, Solar Harvesting is activated.

- *Solar Heating*

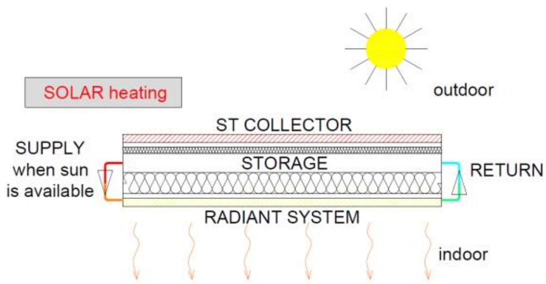


Figure 31 - Façade case study_Solar Heating schematic layout

The loop involves storage tanks and radiant panels of each façade module connected in series. Once the thermal storage is charged, this operation mode allows to deliver the thermal energy produced by the façade to the radiant panel and then to the ambient as radiative heat. The water goes from the hydraulic box (which is connected to the main heating system) to the farther storage (S1) and it comes back to the box by passing through all the storages. Then heated water goes to the radiant panels, which are in parallel, hence the water temperature is the same in each panel. Once the water travels inside the panels, it goes to the main heating system.

- *Solar DHW/Storage discharge*

The loop involves solar thermal collectors and storage tanks. This operation mode scheme is similar to the *Solar Harvesting*, but in addition the produced hot water is delivered to the main DHW system. This operation mode can be used to move the water and avoid stagnation. The same loop could be used during summer to move the fluid and remove excessive thermal energy by pumping into a big centralized water storage system.

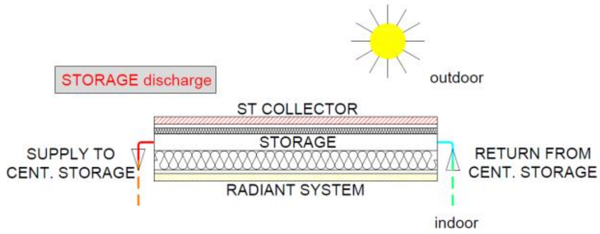


Figure 32 - Façade case study_Solar DHW layout

- *Auxiliary Heating and Cooling*

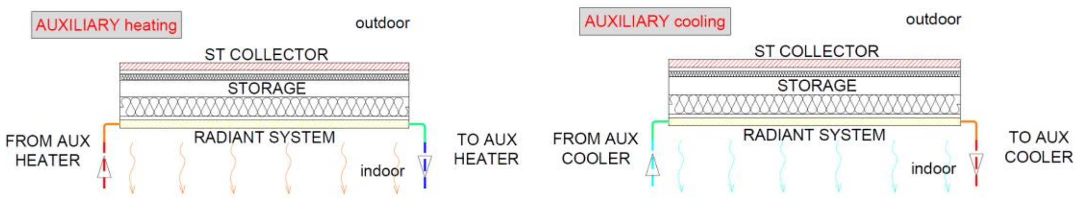


Figure 33 - Façade case study_Auxiliary Heating/Cooling layout

The loop involves only radiant panels. Then water heated/cooled by the auxiliary system goes to the radiant panels, which are in parallel, hence the water temperature is the same in each panel. Once the water travels inside the panels, it goes back to the main heating/cooling system.

3.1.3 General considerations

Among the discussed points during the façade design process, there was the position of the air gap in the façade construction. Two solutions were compared: one with the air gap located between the solar thermal collector and the storage (solar collector as external cladding), and a second one with the air gap between water storage and the insulation layer (solar collector + water tank as external layer). These two scenarios imply different technological solutions in terms of anchoring, position of vapor barriers, dimensions of façade profiles. About the radiant panel, an easy installation and the possibility to inspect the system were the driving keys to find a fastening system. At first, an opening system with small pistons and two hinges along the upper side was thought but such a solution could be too much expensive and not so useless considering the maintenance of the system is occasional. Hence, a cassette fastening system was proposed by the façade manufacturer. Punctual anchoring points are fixed on the façade mullions to bear the weight of the radiant panel. A perimeter crack is necessary to adjust the position of the panel and to allow removal/installation operations. To install/remove two men are necessary. Crucial points were how much space leave between the panel and the insulation, and the length of the flexible tubes allowing the system to be installed and removed. A 'double-shell' system to ease the installation of components behind the radiant panel was proposed by the façade builder (Figure 34). The idea is to include within the façade profile's thickness the radiant system, the façade insulation and the storage. The insulated water storage tank is in line with the façade profile thermal break and it is supported by the mentioned shell made of metal sheet. Spacer profiles between the outer shell and solar collector create the air gap and support the solar thermal collector together with a perimeter frame.

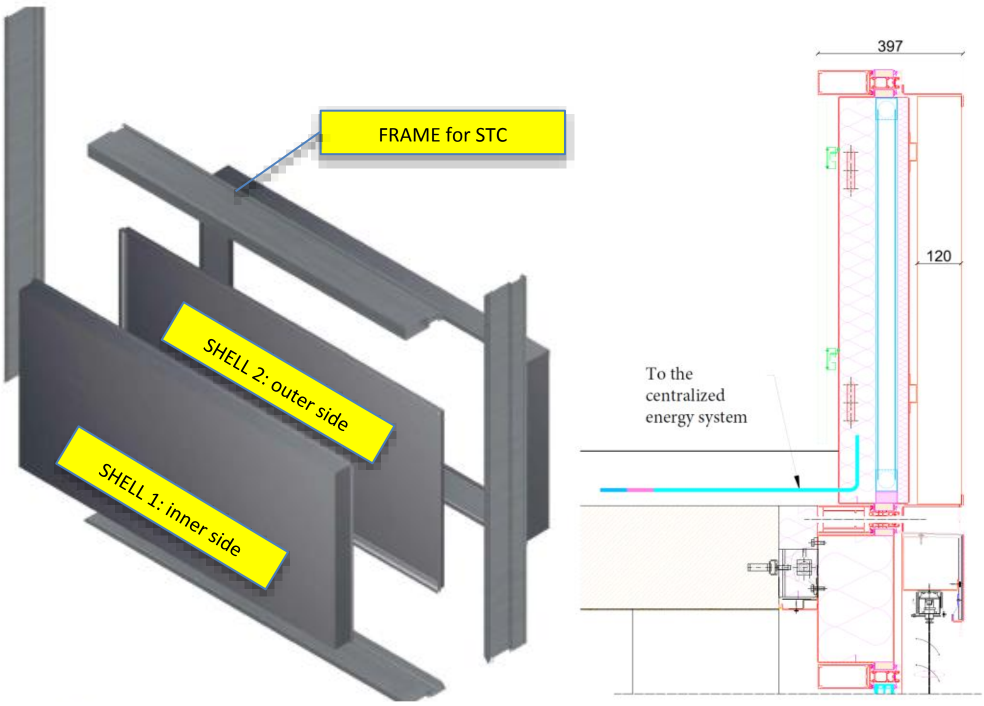


Figure 34 – Façade Case Study_Aluminum profiles and sheets (left); vertical section (right)

Judging the integration level is not an easy task. There are three degrees of integration of a component: application, partial integration, architectural integration.

Application is the level zero integration, namely this refers to not-integrated products like the usual plants installed on flat roofs provided with a steel structure fixed on the slab in order to adjust the slope of the collectors.

Figure 35 – Applied Solar Thermal Collectors [source: http://energyonwi.uwex.edu/photo/solar-thermal-heats-msoe]

The partial integration does not substitute completely the building material. Generally, it is demanded that these systems does not invalidate the aesthetic and functional requirements of the envelope, and over all the energy efficiency of the building.

Figure 36 – Partial Integrated Solar Thermal Collectors [source: http://www.genera.pt/energias/energias-renovaveis/]

Architectural integration is achieved when one can join technical and aesthetic aspects of components with the ones related to the building envelope. When it comes to solar thermal technologies, one must fit the property of the panel to produce energy on the demand site with the aesthetic quality and the properties usually demanded to the building element this is substituting. The building envelope will be considered much more as a contributor to the energy balance of the building.

Figure 37 – Integrated Solar Thermal Collectors [source: http://www.viridiansolar.co.uk/]

The integration of solar thermal collectors into façade systems is still a niche, explored by few people and industries. There are not clear definitions to assess if one is integrating a technology in the right way. A different story concerns the BIPV solutions. For example, in Italy, integration criteria have been established to recognize different incentives/prizes depending on the level of integration (none, partial, total) and to promote innovative solutions respecting the aesthetic equilibrium and the architectural composition [74]. A total integration occurs when the PV panel substitutes a conventional construction component or material and becomes an inseparable part of the building. Therefore, an integrated solar component/material might be defined as a conventional construction component/material producing energy and contributing both passively and actively to the building energy performance. Figure 38 shows a BIPV curtain wall unitized façade where the photovoltaic glass has been installed in place of a conventional laminated glass. Cables run through the façade mullions.

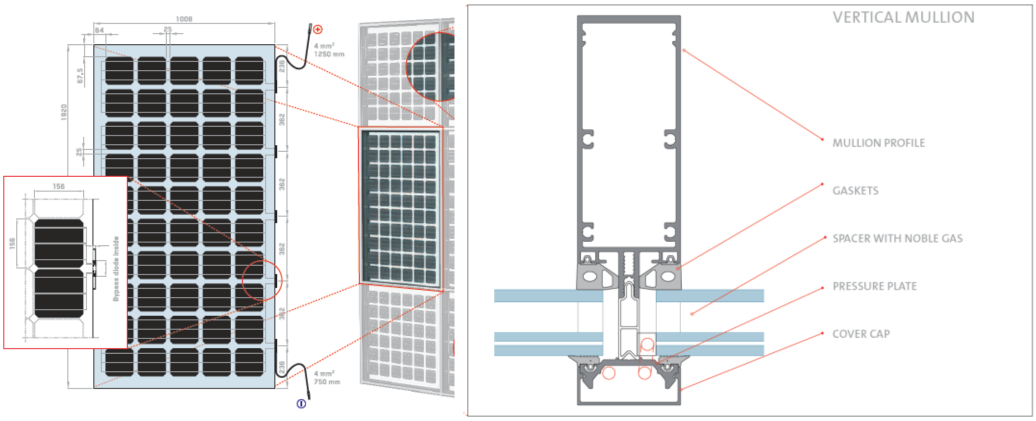


Figure 38 - Details of a BIPV curtain wall façade [source: Sapa Group]

Dealing with building photovoltaic integration is by far easier than solar thermal systems due to the absence of running fluid. Indeed, these imply the integration of pipes as well and consequently a specific space to place them in, besides hydraulic connections and control systems. In order to connect more façade modules from the hydraulic point of view, pipes have to pass through the mullions; hence, drills are necessary before the insertion of components. The same concept has been proposed for the façade case study as showed in Figure 39, where flexible pipes run through the façade mullion for reaching the centralized energy system.

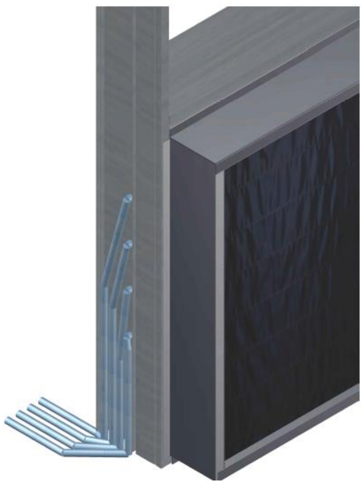


Figure 39 - Façade Case Study_Pipes running through the aluminum façade profile and headed to the centralized energy system

Façade and building services are usually two separated disciplines. Building integrated service façades are solutions combining these two subjects.

The comparison between an integrated solution and two separated systems is very complex. Indoor climate qualities, psychological issues such as control possibilities for the individual user, space needed for ducting, building and running costs, maintenance, warranties and much more should be considered. The concept of decentralized installations is not new, but the application on modern office buildings has only recently become more popular. In order to be independent from the existing structure, it makes sense to fit as many installations into the façade area as possible. The building envelope can provide all vital functions and existing installations can be removed or even left in place.

In order to develop a façade prototype, a configuration of three façade modules connected in series was hypothesized. This assumption was necessary to size pipes, to understand connections and to locate valves and a pump. However, this configuration is quite realistic since three modules bring to a total width of 4.5 meters, which might be a typical office room width. This way, a decentralized system for each office is obtained. More in detail, a hydraulic box is located in the first façade module of each series. This box controls the water flows within the façades and the connection from/to the centralized energy systems for heating, cooling and domestic hot water. Besides single rooms, office buildings are usually characterized by another internal configuration, consisting in bigger spaces called *open spaces.* In this case, a longer series might be necessary.

The performance of a solar thermal façade system has to be evaluated as a whole. The integration of new components in the opaque part cannot justify the negligence of the transparent one since its thermal effect is important as well. Depending on the climate, the internal thermal needs and the façade exposure, a different transparent portion might be necessary.

3.2 Façade design process

The application of a well-known façade system, as the unitized and the stick curtain walls, allows the prediction of the façade performance before the design process is started. The availability of synthetic technical and economic data bridges the knowledge gap between stakeholders. The curtain wall system has reached a state of maturity, but it has taken a long time before it. Nowadays it is structurally optimized and it is therefore virtually impossible to further reduce material quantities. The split responsibilities on the immaterial side help to reduce external risks.

Since the integration of new components in a curtain wall system brings to a new façade kit and a new method of production, a determination of the product type shall be performed for all characteristics included in the standard for which the manufacturer declares the performance. *Determination of the product type* together with *factory production control* by the manufacturer should demonstrate the compliance of curtain walling kit with the requirements of the EN13830 product standard and with the performances declared by the manufacturer in the declaration of performance (DoP). Chapter 6 of the Product Standard EN 13830 points out that the compliance of curtain walling kit with the requirements and with the performances declared by the manufacturer in the Declaration of Performance (DoP) shall be demonstrated by: (i) determination of the product type and (ii) factory production control by the manufacturer, including product assessment. The determination of the product type shall be performed for all characteristics included in the standard for which the manufacturer declares the performance:

- *At the beginning of the production of a new or modified curtain walling kit, or*
- *At the beginning of a new or modified method of production (where this may affect the stated properties)*
- *Whenever a change occurs in the curtain walling kit design, in the raw material or in the supplier of the components, or in the method of production*

Products bearing regulatory marking in accordance with appropriate harmonized European specifications may be presumed to have the performances declared in the DoP, although this does not replace the responsibility on the curtain walling kit manufacturer to ensure that the curtain walling kit as a whole is correctly manufactured and its component products have the declared performance values.

During the design process, many uncertainties can show up. These are related to the chosen materials and their unpredictable behaviors, modeling assumptions and other factors can compromise the performance of a façade over time and causing unattended costs due to a not long-term functionality and failures. For this reason, a team of experts is essential to reduce as much as possible the uprising of failures and a responsible hunt. Except for the client, the stakeholders involved in the façade design stage, responsible of the project success, are:

- *Investor*
- *Project Manager*
- *Architect*
- *Façade manufacturer (design support)*
- *Consultants*

First, client's needs and law energy requirements should be considered. These two aspects draw the façade design. When a general contractor is involved, depending on the contract with the client, he can influence on the decisions in the execution of the façade. Since he is oriented by financial concerns, cutting cost always works to his benefit. This means more potential conflicts between the parties.

Simple tools like façade configurators (façade fronts to be composed in terms of windows, opaque passive and active panels, active technologies with performance and costs, performance drop overtime) should be spread and become daily used instruments. Calculation tools to assess the affordability of the solution in comparison with standard schemes are needed if we want the stakeholders to communicate with the same language.

During the design concept stage, tools are needed to:

- *Facilitate integrated design approach early in the design phase*
- *Facilitate communication between building services engineers and architects*
- *Help communication between clients and the design team*

If the designer is provided with an indication of how efficient refurbishment options are, it is possible to apply them as part of an integrated strategy rather than try to add measures in later stages, after the strategy is developed [75]. A correct energy efficiency strategy should follow these three steps:

1. *Reduce energy demand*
2. *Apply renewable energy sources*

3. *Efficient use of auxiliary energy: provide intelligent control of the system including demand control of heating, ventilation, lighting and equipment.*

The future strict energy requirements will boost the integration of systems and technologies into the façade. Solar thermal roof installations must not be avoided, but when it comes to high-rise buildings, the roof area becomes small in proportion to the usable floor area and the façade surface area. The climate characteristics of the building site are essential to understand the chances to design a responsive building. The climate data is useful not only for estimating the heating and cooling load of the building, but also for creating passive design concepts.

Paul Denz, of the Façade Lab [76], sustains that “façade collectors are often viewed as additional measures for the façade and thus lie in competition with other heating systems instead of other façade solutions. Indeed, they must satisfy the boundary conditions of the construction project, the overall concept of the architects and the wishes of the client.”

A crucial phase is the assessment of façade systems during a call for tender to award the best design (submission stage). Very hardly the client can evaluate how good is the façade system proposed by the designer. Most of the times no technical data are shown. Tillmann Klein [2] interviewed both architects and façade builders of the German-Dutch area to investigate when the different stakeholders are involved during design and construction processes of façades. How the façade builder is involved before the tender process can be a crucial point. As shown in Figure 40, designers are involved in consulting the client from the preliminary stage until the assembly of the façade on the building site.

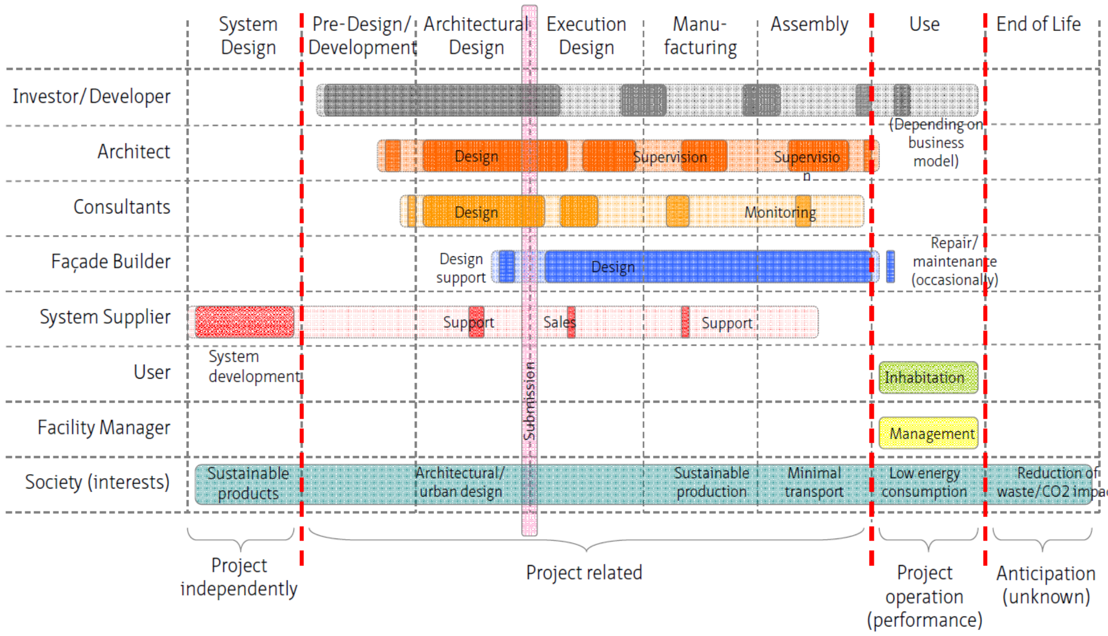


Figure 40 - Involvement of stakeholders during the façade design chain [2]

It is a key-element to understand if façade builders are involved in the process before or after the definition of technical specifications. Before submitting the project to local authorities for the approval, all of the technical details of the construction are specified and the tender documents are created. If the façade builder is asked to conduct the executive design, after the technical specifications have been defined, he does not have so much influence in the project. He should be involved before writing the specifications to impact the design. Furthermore, Klein investigated whether the façade builder is involved or not in the design process before the tendering phase. It was highlighted that façade industry sees the biggest potential in an early involvement of their discipline, or even better, a direct contract situation. Involving the façade builder before specifications are written seems to provide the best opportunities for innovation. Usually façade builders get an involvement in the tendering procedure as advisers and sellers, but not as designers. “Once the façade builder is concretely involved in the process, he deals with the execution design. Generally, every façade builder conducts two or three design phases. Results of each design phase need the architect/consultant for approval. Finally, the production and assembly design phase starts. Although the design is often based on existing systems, the façade builder draws every profile, every gasket, and every slot he has to drill. He needs to know the glass properties, glass sizes and weights. Structural calculations have to be done. He also needs to adhere to order and delivery times.”

Since the façade surface area is one of the main responsible for the living/working comfort in buildings, monitoring of performances should be inserted in the specifications, especially when complexity increases and building services and façades are combined. The responsibilities in case of failure have to be clearly stated. Maintenance and cleaning are considerable costs issues that must be accounted for in the early design phases. The type of investment to maintain and clean the façade should be done beforehand to prevent high cleaning costs.

When it comes to complex façade systems, complications might come from the schedule of the different components suppliers. For the façade case study, object of this thesis, the involved stakeholders during the production process are:

- *System house: company supplying profiles, gaskets, weather strips*
- *Solar thermal collector producer*
- *Water storage tank producer*
- *Radiant system producer*
- *Façade manufacturer: assembling the finished product*

When a system house supplies components to a façade manufacturer, who in turns assemble everything, it is mandatory an agreement (a contract, a license) containing clear provisions with regard to responsibility and liability of the component producer. The system house may take the responsibility for the determination of the product type regarding one or several essential characteristics of a product, then manufactured and/or assembled by other firms in their own factory. The concept of cascading determination of the product type might be taken into consideration in the technical specification. A notified product certification body or a notified test laboratory intervention is necessary. At that point, the manufacturer assembles the product in the same way as that for which the system house has obtained the determination of the product type report. Otherwise, he needs to submit his finished product to the determination of the product type. The manufacturer assumes the responsibility for the correct assembly of the product in accordance with the instructions notified to him by the system house. In case of curtain wall-kit produced as a one-off, prototypes or products produced in very low quantities (less than 150 m²) the procedure is different. The test samples shall be representative of the intended future production and shall be selected by the manufacturer; the results of the assessment may be included in a certificate or in test reports issued by an involved third party. If there is the intention to move to series production, the initial inspection of the factory (production line) and Factory Production Control shall be carried out before the production is already running and/or before the FPC is already in practice.

Façade manufacturers not considering the foreseen change in terms of energy requirements will be partially cut out from the market. Only if they set their organogram now, before the entry in force of laws, they will be able to face new issues related to new façade concepts or even not new but involving water and air-based systems.

It is quite hard understanding where the potential for cost saving, hence for profit, is located for façade builders. Replicability might help to find an answer, but a sufficient know-how is necessary to build a catalogue of façade products. New processes require a learning phase. This is hard to see in façade industries. Each time there is a need for changes and adaptions of existing systems. Nowadays a good part of the total cost of a unitized façade system is due to the material procurement, but it might be that, due to bigger complexity of active façade systems, the design and engineering will gain a higher share out of the total cost.

One of the two interviewed façade companies gave his take on the organogram of an enterprise dealing with a new potential market like the one of solar thermal façades. To integrate a department dealing with solar thermal façades in his company, 3/4 new figures would be necessary:

1. *A person facing thermal engineering issues (TE), hence solving the hydraulic layout inside the façade and related connections to the centralized building energy system. He should also set up the controls to activate the integrated system.*
2. *An energy modeller assessing the impact of high temperatures systems in order to evaluate risks for both thermal expansion of façade components and for user's comfort through simulations (Sim). This person might be a researcher and the collaboration with the thermal engineer is paramount to assess the feasibility of the whole façade system.*
3. *A plumber to practically build the hydraulic boxes and pipes' connections*
4. *An electrician dealing with electrical staff inside the façade (this figure might be already within the staff)*

This new personnel should cooperate with the technical staff (civil engineers, sales managers to keep contact with possible components suppliers and to understand the marketability) already present within the firm to understand how and where pipes and hydraulic components can be located inside the opaque façade portion.

New high-qualified employees lead to new costs for the façade entrepreneur. More in detail these costs can be included in engineering/design component of the final façade cost. Indeed, the cost of a façade system is the sum of four major items: engineering/design, material procurement, production, logistics (including transport and installation/assembly). The quantification of the cost related to the new involved figures is showed in the paragraph **Error! Reference source not found.**.

3.3 Operation and maintenance

Nowadays designers, façade manufacturers and component suppliers are more aware about the operation stage and the end of life of building components. Technologies, their performances under different conditions and the required maintenance are all aspects to be considered when investigating the business concept behind complex façade systems. This paragraph focuses on the priorities to take care of when solar technologies are integrated in façade.

Building retrofit strategies based on replacing old mechanical systems with new, more efficient ones, that exploit renewable energy sources are common. However, this single-product approach is not the solution to achieve the energy efficiency in buildings. Indeed, the performance of individual elements often depends heavily on the performance of the system they are part of; i.e. the performance of a heat pump depends on the performance of the whole heating and cooling system, which requires an energy source and distribution and delivery devices. Innovations are shifting from component level to system level. Buildings have become integrated concepts in which advanced systems work together to reach an optimal performance for energy consumption, comfort and health. Integrated concepts can only be made real if durability of all the components is assured.

The potential for technical failures linked to solar façades scares designers and façade producers. That is the reason why innovative façade concepts have high cost of production and installation. It can be assumed that most of the failures occurring to standard STCs can appear also to products integrated into façade. Modern, high-quality solar hot water (SHW) systems are reliable and long-lasting if designed and installed properly. Many systems installed more than 30 years ago are still going strong. Experienced technicians use their senses to determine the status of a solar water heater. Unusual, high-pitched noises and burning odors are associated with bearing wear from the pumps. Burning smells can also indicate electrical problems, such as loose connections or damage from excessive voltage or current. Visual inspection can reveal controller malfunction, leaks, and fluid levels [77].

Differently from façade integrating Photovoltaic technologies, requiring some cables to connect modules and a storage system (battery) to be located somewhere within the façade thickness, solar thermal façades imply more complications. Indeed, the integration of several hydraulic components besides the resolution of issues such as water pressure, possibility of noise due to water flowing into the façade (maximum water speed) and the weight of the whole system are just a few of the issues to be faced. The façade case study helped a lot to recognize the difficulty of creating a hydraulic box and a distribution system as much compact as possible with the chance to disconnect a single module from the others adjacent.

The durability of curtain walling kits depends on the long-term performance of the individual components and materials as well as product assembly, its maintenance and the service environment. Specifications and classifications for individual materials and components have to be found in their standards. When components generating heat (solar thermal collectors) or having fluids flowing in (ducts, storages) are integrated in façade, unusual temperatures might occur. For this reason, the study of the physics of the façade helps to assess the durability.

3.3.1 Durability and failures

A crucial aspect in solar thermal façades is the maintenance required to assure the operation of the system. More specifically, the duration of components, the accessibility for inspection of the façade (by guarantying façade requirements) and the responsibility in case of failure are the main concerns. Due to water flowing into the façade, the potential noise is something to pay attention to. Even if installations on façade are limited, lesson learned from standardized roof applications can be a driver in designing envelope-integrated solutions. Components failures are pointed out as the main problem, while installation and maintenance practice is not a frequent source of system's failure. Controllers and sensors are the major component problem, and pumps are second [77]. Liquid-based STCs involve the use of electric pumps, valves, and controllers to circulate water or other heat-transfer fluids through the collectors. Antifreeze fluids degrade over time and these should be changed every 3 to 5 years [3]. These are all aspects to be considered if STS are integrated into façade systems in order to guarantee their inspection and potential removal/substitution. Typical liquid-based STCs are glazed flat-plate, unglazed flat-plate and evacuated tubes. STS are provided with air vents, located at the higher part of the plant to evacuate possible air bubbles created inside the pipes. It is fundamental avoiding that heat carrier vaporized during stagnation goes out through these valves.

Solar Thermal Systems (STS) are characterized by a fluid energy carrier that might be subject to phase variations: from liquid to vapor and vice versa. These variations have to occur within certain limits; indeed excessive temperatures could damage components. Main aspects to take care of are the glycol, used as freeze protection, and the pressure the system is subject to. Concerning the glycol, this must not become too acid (pH should be always higher than 7) because of the evaporation, otherwise corrosion of pipes is likely to occur. Many recent applications are characterized by the use of gas (including pentane) as fluid, allowing to avoid the stagnation due to their natural behavior of evaporating only within a specific temperature range, where the maximum value is lower than the stagnation temperature; over a specific temperature, the process is automatically blocked. Another problem is the material sediment inside pipes included in evacuated systems; the oxidation of the glycol due to chemical reactions can bring to pipes clogging.

Since a glazed flat plate collector is installed in the façade case study, here follow only potential failures associated to this technology are reported.

Glass breakage. This is one of the most frequent issues, associated also evacuated tube collectors. While the glass can be replaced by removing the collector trim, finding a source of low-iron tempered (LIT) glass can be difficult. Shipping a single piece of glass can be expensive—sometimes more than the glass itself. Because of this, most people opt for common tempered glass. Tempered glass cannot be re-cut, so exact measures are needed. Broken glass should be replaced quickly or additional damage to the collector can result from wind and rain. The gasket around the glass can most often be reused.

Figure 41 - Corrosion of a STC’s components after the glass cover is broken [77]

Condensate accumulation. All collectors will exhibit some condensate on the glass intermittently, but if it is present all the time, standing water may be accumulating in the bottom of the collector. The remedy for this is drilling 1/8-inch weep holes in the bottom corners of the collector, away from glass and tubes.

Absorber coating deterioration. If copper or aluminum shows up through the absorber’s paint or coating, it should be repainted. The original coating may have been a selective surface like black chrome but that will be impossible to replicate in the field. Semi-selective paints are available online but difficult to apply without experience.

High collector glass temperature. This issue can takes place if joints are not well welded or a low flow rate through the collector occurs. Low-temperature welds to bond copper tubes to the absorber plate can bring to the separation of joints, after years of repeated heating and cooling cycles. A collector with a not bonded absorber will be very hot, and the temperature difference between the supply and return lines will be small. Much of the heat in a collector with a not bonded absorber will be reradiated through the glass. In this case, absorbers need to be replaced with an identical one. Otherwise, the entire collector will need to be replaced. Concerning low flow rates, high temperature difference between supply and return piping can happen due to installation design flaws, an undersized pump, a partial pump failure, or a restriction in the piping, heat exchanger, or collector tubes. Pump problems may require the removal. The orientation of the pump is another aspect to pay attention to.

Leaks. This issue is mostly due to freezing. Freeze breaks in the absorber tubing should be repaired by brazing or silver soldering. The silver solder process is easier than normal soft soldering used on pipe joints and the copper tubes don't require a bright fluxed finish to seal the leak. Soft soldering inside collectors is not suitable due to the lower melting point of the solder.

Solar loop controller. Cold supply and return pipes are a symptom of no flow, hence the pump or controller should first be checked. Both pipes being hot and at the same temperature is likely only to occur in a system with an external heat exchanger. This indicates that the collector loop pump is operating and the controllers have turned it on but that the heat is not being exchanged to the home's potable water. A malfunction in the domestic hot water (DHW) pump or an obstruction on the DHW side of the heat exchanger is indicated. The orientation of the pump is not insignificant. Indeed, a vertically oriented pump increases wear and tear. Pumps should always be mounted with the motor axis horizontal [77].

Due to the specificity of façade systems integrating hydraulic or aeraulic components, it is hard to find information related to these aspects framed in the façade sector; prototyping and testing phases should be promoted to verify and, in case, to solve these issues. Usually active components have a different durability, shorter than the façade's durability; indeed, after 20 years or even less, there might be components' substitution needs. The temperatures achieved by the solar thermal collector and storage systems integrated into the façade thickness can bring to the deterioration of components like gaskets, sealants and insulation.

Once again, the product standard EN 13830 can be used as reference to apply the basic approach to durability. Components of the curtain walling kit shall be categorized as follows: primary and secondary components. Primary components are those with a predicted service life greater than the design life of the curtain walling kit without the need of maintenance, other than regular cleaning. Secondary components have a predicted service life lesser than the design life of the curtain walling kit, assuming regular cleaning and maintenance in accordance with information provided by suppliers. A correctly designed and installed curtain wall can have a service life of 50 years but some components will require repair or replacement during the service life of the curtain walling kit as reported in the following list [78], [79]:

- *Gaskets (secondary): 10-15 years (substitution)*
- *Sealants (secondary): 10-15 years (substitution)*

Interior seals around infill panels only if the panels are removed. When vision units are replaced, any wet interior seals are automatically replaced as part of the work. As part of a project involving glass replacement, it is advisable to re-seal all corner blocks at the bottom corners of the frame openings to receive new glass.

- *Fixings (primary): 50 years (substitution)*
- *IGU (secondary): 25 years (substitution), 1 year (cleaning)*

- *Framing members (primary): 50 years (substitution)*
- *Insulation (secondary): 30 years (substitution)*
- *Hardware for openable infills (secondary): 15 years (substitution)*
- *Hardware for framing members (primary): 50 years (substitution)*
- *Aluminum sheet (finishing) (secondary): 30 years (substitution)*
- *Solar thermal collector (secondary): 20 years (substitution), 1 year (cleaning)*
- *Electronics/controls (secondary): 10 years (substitution)*
- *Water tank storage (secondary): 15/20 years (substitution), xx years (inspection)*
- *Radiant system (secondary): 30 years (substitution), xx years (inspection)*
- *Valves (secondary): 20 years (substitution), xx years (inspection)*
- *Pump (secondary): 20 years (substitution), xx years (inspection)*
- *Ducts (secondary): 50 years (substitution), xx years (inspection)*

This lifespan regards standard applications on façade. Since active façades can reach higher temperatures and heating/cooling cycles, their durability could be lower. Figure 42 shows the temperatures of the façade case study during a summer day (Outdoor Temp. 35°C, Indoor Temp. 26°C) with charged thermal energy storage (a heat source was set to achieve a water temperature of 90°C).

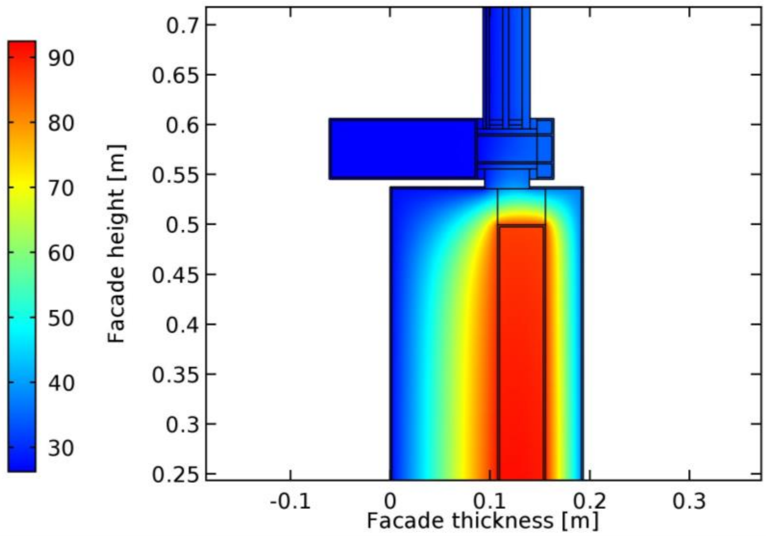


Figure 42 – Façade case study_Façade temperatures during a summer day with TES charged

Under these assumptions, façade components like gaskets and sealants do not achieve temperatures higher than 40°C. Silicone and rubbers (used as gaskets) can resist to temperatures higher than 100°C as reported in Table 4, so this should not be an issue. One more time, the insulation around the storage system can be subject to continuous heating/cooling cycles, leading to a reduced lifespan. Glass spacer and the insulation layer of the solar thermal collector installed on façade can be subject to thermal fatigue and lose their efficiency.

Table 4 - Tolerable temperature of different materials used as sealants and gaskets [P. Rigone, Progettazione e posa in opera di elementi di facciata, 2014]

Material	Temp. Min [°C]	Temp. Max [°C]
EPDM	-20/-35	130
SILICONE	-20/-30	80/95
NEOPRENE	-60	180
Thermoplastic Rubber	-40	120
Melt Processible Rubber	-40	120
PVC	-20	70

Several façade boundary conditions have been simulated in stationary mode to quantify the heat flux through the façade and the potential risk of surface condensation. Figure 68 reports the temperature trend at two different heights within the façade thickness during a winter sunny day with discharged storage. Boundary conditions and heat sources are:

- *Indoor air temperature=21 °C;*
- *Absorber temperature=90 °C (solar thermal collector is heating up);*
- *Outdoor air temperature=0 °C;*
- *Water storage heat source=0 W*

The maximum air gap temperature is around 10 °C, while the maximum water storage temperature is 12 °C. Condensation on the inner cavity surface is likely to occur. Indeed, a minimum surface temperature value of 2.95 °C was computed. Airflow temperature around 9 °C and 70% relative humidity would lead to condensation. This would not be a problem since it is external and aluminum sheet is impermeable to water. Condensation on the STC glass cover should occur only with cold and humid external air conditions, but it is not a relevant issue, except for the aesthetical aspect. Air gap temperature increases of 5 °C, passing from 5 °C at 0.20 m height to 10 °C at 0.80 m height.

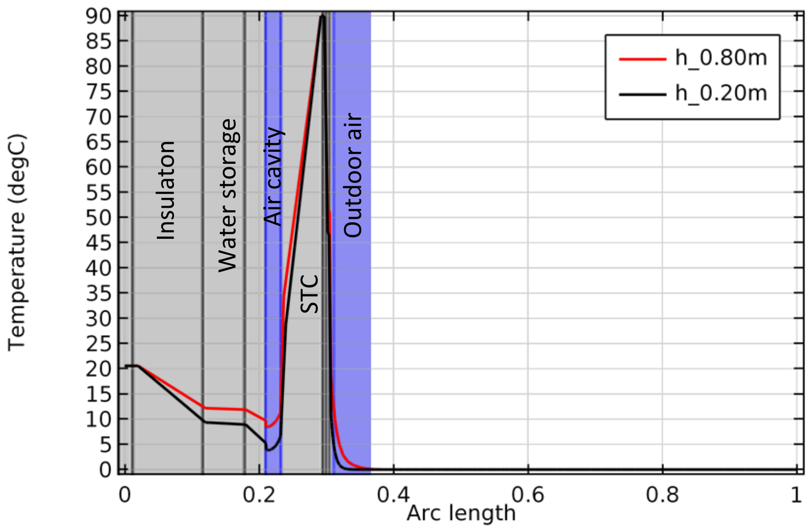


Figure 43 –Façade case study_Façade temperature trend at different heights during winter with discharged TES

Enabling water and vapour management within the façade construction is considered a secondary function according to the three types of functions defined by Poelman in *Technology Diffusion in Product Design* recalled by Tillmann Klein [2]: primary, secondary and supporting functions. Secondary functions are necessary to create a durable construction (which is a primary function). Allowing an interior drainage is considered a supporting function. When it comes to curtain wall façades, the glass and metal components are impermeable to both liquid water and to water vapor flow. In a face-sealed wall the outer metal and glass surface form a near continuous vapor retarder on the cold side of any insulation with no provision for drainage. In designs where this condition is recognized, vapor retarders are also provided on the warm side of the insulation, usually in the form of foil-backed insulation to minimize the risk of condensation formation in the components exterior to the insulation. Some systems with internal drainage similarly incorporate an interior vapor retarder. These systems obviously benefit from the condensation drainage path provided by the internal guttering system but create the risk of corrosion or mold. After water penetration, condensation is the most often reported performance issue. The control of heat flow and condensation resistance is closely related. Effective thermal breaks that retard heat flow from warm (interior) to cold (exterior) will help to boost frame surface temperatures [78].

In solar thermal façades, the flow direction could be reversed due to the production of thermal energy on the cold side. Several works regarding heat transfer in solar thermal façades can be found. While, according to the literature, vapor transfer is not a matter of concern and for this reason is not reported. Cappel et al [53] remember that the direction of vapor transfer can change because the outer layer of the wall is heated and reaches high temperatures. In this case, vapor should be able to exit the wall to the interior of the building. This is why the inner layers should be more open to diffusion for integrated systems. As an example, they reported that the measurements of Bergmann and Weiss on a wooden and a concrete prototype façade did not reveal any critical condensation in any layer behind the glazing or the absorber.

One of the obstacles for the designers in considering these façade-integrated solutions is the lack of knowledge about the building physics. For example, for regular collectors installed on the building skin and separated from it by a ventilated gap, one might neglect the heat transfer towards the building. The situation is different when the collector is integrated into the wall structure. Heat losses of the collector can be lower due to a higher temperature than ambient at the rear side of the collector, which in turn means reduced heat losses in winter due to a heated wall. On the other hand, a flux towards the occupied building space during summer can occur and cause thermal discomfort due to a higher temperature besides the risk of increasing the cooling energy demand. Attention to active components in contact with passive components should be paid. In case of a wooden frame, this can decay or even slowly turn into charcoal, which means a loss of stability for the building. Depending on the presence of an air cavity behind the collector, high temperatures, up to 195°C, can be reached in spring and autumn during stagnation. As studied by Stadler [19], façade collector absorber's temperature can easily go over 100°C; the same study evidenced a 25 W/m² heat transfer through the wall inwards when collector is hit by solar radiation in March.

Solar thermal façade systems still show uncertainties to be faced. Among these, there are: (i) the system performance guarantee over time, (ii) the responsible figures in case of failures/damages and (iii) a certification product/labelling procedure. The client should be assured about the expected productivity of the façade-integrated system; performance drop over time is normal but the entity is not easily quantifiable due to few installations and the lack of test methods for

BIST products. Management risks are possible if responsibilities are not clearly defined. New certifications and related procedures might be necessary for façade builders.

Besides these aspects, health issues could also show up. Risks due to incubation of bacteria legionellae in systems are possible. It is necessary to ensure protection against the proliferation of bacteria. This bacterium is widespread in nature, mainly in water, flourishing at temperatures between 32 and 41°C. Lukewarm water can remain for several days in storage tank. Guidelines (ASHRAE Guideline 12-2000) recommend that to destroy the Legionnaires bacteria the temperature in the hot water tanks should be heated to 60°C at least once a day.

Finally, commissioning should be promoted more and more as a way to improve energy efficient solutions. On one hand, this item represents a new cost, but on the other hand is a benefit since reduction of costs during the operation phase of the building are foreseen. Tender procedures should include the commissioning as requirements to get some points when a new call for design is open.

Commissioning is a risk management strategy that should be implemented to each systemic approach aimed to get the predicted energy savings and emissions reduction. In a few words, commissioning helps to assure the owner to obtain the performance he paid for. It is about a procedure to identify and correct problems otherwise discovered over time and leading to bigger maintenance costs and safety issues. To raise the awareness about this thematic, information concerning standard for calculations and measurements of façade performances (both in laboratory and on site) could be provided from the commissioning body to those who participate to a call for tenders. In many countries there is the International Performance Measurement & Verification Protocol (IPMVP), which provides procedures able to measure accurately the savings through the use of standardized measurement protocols. The same goal can be achieved through the Metering application, which is another measurement system [80].

For the HVAC system, the following actions are recommended:

- *Direct observation (schedules, operation function without variable speed)*
- *Witness testing in factory (pressure inside tubes, pressure drops)*
- *Test extremes and crash-recovery (pumps and fan velocity)*
- *Check scheduling and resets match specifications*
- *Verify the right sizing of components*
- *Assure the correct positioning of control sensors*
- *Check the coupling between controls and informatics*

Regarding envelope components:

- *Verify the correspondence between prescribed and installed materials*
- *Check both design and installation to avoid humidity appearance and thermal discomfort*

Table 5 reports the main reasons of energy inefficiency in commercial buildings in the United States. First causes are due to losses in ducts and energy plants (HVAC and Lights) left switched on when buildings are not occupied. Hence, these sources are not closely related to the building envelope, unless energy systems are integrated into façade and the same issues can occur.

Table 5 – Main causes of energy inefficiencies in commercial buildings in the US

Top faults causing energy inefficiencies in commercial buildings (Top 13 of 100+ faults identified)

	National Energy Waste (Quads, primary/year)	Electricity equivalent (BkWh/year)	Cost ($billion/year)
Duct leakage	0.3	28.6	2.9
HVAC left on when space unoccupied	0.2	19.0	1.9
Lights left on when space unoccupied	0.18	17.1	1.7
Airflow not balanced	0.07	6.7	0.7
Improper refrigerant charge	0.07	6.7	0.7
Dampers not working properly	0.055	5.2	0.5
Insufficient evaporator airflow	0.035	3.3	0.3
Improper controls setup / commissioning	0.023	2.2	0.2
Control component failure or degradation	0.023	2.2	0.2
Software programming errors	0.012	1.1	0.1
Improper controls hardware installation	0.01	1.0	0.1
Air-cooled condenser fouling	0.008	0.8	0.1
Valve leakage	0.007	0.7	0.1
Total (central estimate)	1.0	94.6	9.6
Total (range)	0.34-1.8	32.4-171.4	3.3-17.3

Adapted from Roth et al. (2005) assuming 10,500 BTU/kWh, and $0.10/kWh

According to a LBNL research, commissioning involves costs in the range of 2 €/m² (for existing buildings) and 9 €/m² (for new buildings). These costs were obtained by converting the values found in [81] with an exchange rate of 1.40 (2009). For new buildings, an incidence of 0.4% over the whole building cost can be considered. Energy savings between 13 and 16% were achieved averagely. The payback time of this extra investment is in the range of 1.1 and 4.2 years.

3.4 Economics of a solar thermal façade

In this paragraph a critical analysis of both the design and the construction process is reported to understand where the potential for cost saving is located. Finding the relation between a façade cost composition and risks is not an easy task. To give a complete frame of the potential involved risks, a matrix correlating uncertainties during the different stages of the design process and costs was elaborated. The cost analysis of the façade case study shows where it might be expected an increase of expenses along the design, production and installation process of the façade elements. Cost increasing factors were applied to quantify the risk profit associated to solar thermal façades. The analysis and the assumptions have been double-checked with an engineer from Stahlbau Pichler.

Can solar thermal façades become an affordable solution in comparison with standard passive façades? Since most STFs are prototypes, it is difficult to get reliable data on the payback period for such systems. Cappel et al. [53] estimated the cost of some Solar Thermal Façades starting from the prices (including labor costs, excluding VAT) of standard passive solutions. The costs are 90 €/m² for a regular composite insulation system and 240 €/m² for a wooden façade with vacuum insulation panels. The prices with integrated absorbers behind customized glazing are 390 €/m² and 600 €/m² respectively. This gives an investment for integrated solar thermal façades that is between 150% and 333% higher than for standard wall constructions. Unlike solar thermal systems installed on the roof without any integration criteria, the cost of façade adapted solutions depend strongly from the façade typology (lightweight or heavyweight structure) and the solar thermal application (DHW, combisystems). The other crucial aspect is the climate of the location. A metric to assess the economics of solar thermal façades is the payback period, which is dependent on the initial investment and the cost of alternative energy. Since Solar Façades represent a new frontier, many uncertainties regarding manufacturing, materials and installation can occur during economic estimations. These can lead to underestimated or overrated costs. Furthermore, the cost of fossil fuels and electricity varies from country to country, so payback periods cannot be extended even in the same climate zone. Even if it is about a different technology, Buonomano et al [82] calculated the cost payback time of Building Integrated Photovoltaic Thermal (BIPVT) solutions by varying the thermal resistances and capacitances of the building envelope in different climate zones. For the investigated case studies, the pay back periods appear quite long, varying from 11 years for South European weather zones to 20 for North European ones. O'Hegarty et al. [20] compared a massive solar thermal collector (MSTC) with concrete as absorber material and pipes embedded in, and an unglazed collector with copper-based absorber. These two systems are thought for low temperature applications. Depending on the scale of the project in question the cost of an 80 mm thick concrete wall would range between €(4–6)/m², whereas a 0.5 mm thick copper wall could range between €(30–100)/m². Assuming the piping system for both systems is the same, the cost of an UC is approximately 10 times that of an MSTC. An additional glazing layer would add an extra €(4–20)/m² onto the cost, making Flat Plate Collectors approximately 13 times the cost of MSTC.

Besides the comparison with fossil heat generation, a competitor of STSs to produce hot water is the electrical heating from PV panels coupled with heat pumps. A cost analysis comparing solar hot water generation with electrical hot water heating for a single-family house, showed that the first system can compete extremely well, even if it still requires a subsidy[70]. This is related to standard energy systems not integrated into the building envelope. When it comes to façade integrating active solar technologies the comparison might be not so predictable. Indeed, compared to a traditional passive wall or façade, more suppliers are involved in the design and production process of an active façade, hence extra costs are introduced. The higher initial cost in comparison with standard façade products can be overcome through alternative financing models and support schemes. The goal is to pay back the delta cost within the duration of the warranty (usually 10 years).

A system helping the diffusion of solar thermal façades might be the E.S.Co. The typical customers of Energy Service Companies (E.S.Co) are energy-intensive users like big industrial buildings or obsolete energy systems. Rarely they provide a service for those who have an energy bill lower than 50,000 € or for projects where payback time is longer than 20 years [80]. If the client is suited for the energy retrofit, several risks are considered within the audit. Technology, operative, norms-related, market and financial risks are investigated. Net Present Value (NPV), Profitability Index (NPV to initial investment ratio), Payback Time and Internal Rate of Return (IRR) are the main economic performance indicators used by E.S.Co. There are three ways to finance a retrofit action:

- *E.S.Co uses proper capital or deriving from leasing*
- *The client uses its own money or the one coming from banks*
- *Third-party financing*

The Directive 2006/32 /CE defines the last option. The third party charges the beneficiary a fee equivalent to a part of the energy savings achieved as a result of the measure. An Energy Performance Contract has to be signed between client and E.S.Co. The client pays a rate for the entire contract's duration, which is equal to the energy bill increased by a proportionate share of the profitability of the intervention, the duration of the contract, the risk assumed by the parties. The E.S.Co. is committed to ensure a certain level of energy savings by remedying the customer from technological risks. While the customer assumes the financial risks, the E.S.Co. assumes the risks for the performance, and it has to cover or acquire the difference between the savings achieved and those planned.

Lessons can also be learned from the other diffused solar technology, the photovoltaic. Different financial mechanisms have been introduced some years ago to promote the installation of PV systems. Leasing and Users Efficient System are just two of these mechanisms [83].

Leasing: in the US, two thirds of the residential PV plants were installed by following the third party ownership model. A credit body, like a bank, takes charge of the initial investment as a unique owner. Meanwhile the user takes advantage of the PV plant and pay back the investment to the bank through a monthly payment. As long as the credit body is the owner of the system, it receives the potential incentives, tax relief or electricity credits. On the other hand, the clients save the necessary investment at time zero and furthermore, and don't have to think about bureaucratic and maintenance practices. Once the investment (plus interests) is paid back, the energy system becomes property of the user. Two procedures can be followed: the Power Purchase Agreement (PPA) and the Real Leasing. The PPA allows the client to buy the electricity at a predefined cost, lower than the one of the electricity from the grid. The agreement has a 20-year duration. Second option is about the monthly payment allowing the user to ransom the PV plant. The amount of the monthly payment is calculated by considering the consumption before and after the installation, and prices are blocked over time.

Users Efficient Systems: this model is based on the availability of grounds where PV plants can be installed. This open field systems are only thought to the own-consumption. Mediation through energy companies is excluded. The person who wants to join the system is obliged to buy the electricity from this plant for a minimum number of years in a way to guarantee to the 'producer' the initial investment return. Advantages linked to this system are: the payment of a tariff without burdens for transmission and distribution; the use of clean energy; an electricity market meeting the local demand and offer.

Extending one of these mechanisms to active façade systems might be not immediate, but it is paramount working on it. Starting from the building scale, the façade value depends primarily from the investment, hence from the available budget. Since façade protects the building itself and those who stay inside, the use of the building is strongly affected by the envelope performances. As stated by den Heijer [84], façade-related investment can be more than 50% of the whole construction cost of a building. To assess the façade value, one should evaluate how façade:

- *support user activities, improve user satisfaction, add productivity (functional value – operational level);*
- *affect life cycle costs and add profitability (higher benefits from renting, lower management costs, …) (financial value – strategic level);*
- *reduce energy use, improve technical conditions, contribute to ecological goals, contribute to cover the energy demand (energy value – operational level);*
- *add competitiveness and improve organization identity (image, market share) (strategic value – strategic level).*

As described in paragraph 3.1, the façade case study is a curtain wall unitized system. When active components are introduced in the façade production chain, due to the failure risk and the lack of knowledge, one might overcharge the usual margin on the supplied material. This would make the market of active façades not competitive. According to the interview carried out by Klein [2], "façade builders seem to fear the problems that result from external communication and physical dependencies or such that relate to other parties on the construction site than internal planning mistakes, wrong cost calculations or evaluation of the task." He also questioned if the façade builder should become the builder of new installations or the integrator of such subcomponents, but it seems that more technical knowledge would be necessary in design offices.

3.4.1 Façade cost composition

The integration of more functions such as an active contribution to the building services is expected to increase the importance of façade cost in relationship to the whole building construction cost. Currently, unitized systems account for 20-30% of the costs of a building. With the tendency toward unitized systems, more effort is shifted to design and production. Also material costs will be rising, simply because of more complex systems. Figure 44 shows the façade cost composition in terms of design, material procurement, production and logistics (transport and assembly) according to three façade builders whose company is based in the province of Bolzano (Italy).

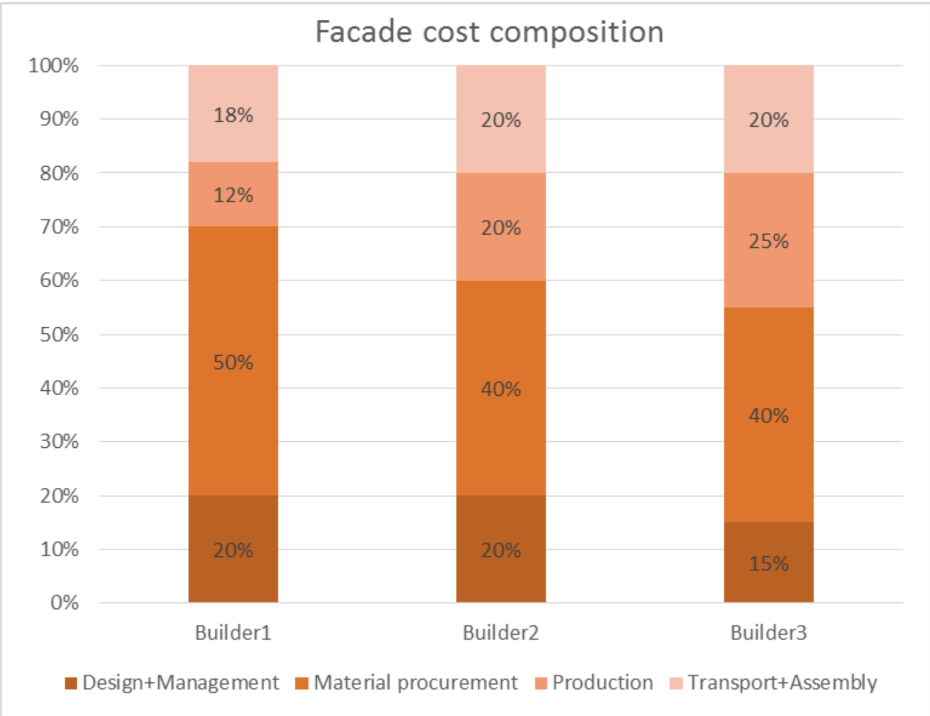


Figure 44 - Façade costs by categories according to three façade builders (South Tyrol)

It can be observed that material procurement is the main cost item in the façade cost, ranging between 40 and 60%. Design and production account for 25 to 40%. This aspect might reflect the complexity of the solutions usually produced by the façade builder. What is really hard to detect is the risk associated to façade systems. Coefficients to be applied to the cost over the façade design/production chain should be found according to the experiences of façade builders if they used solutions more than one time. A Learning Curve could be then traced and applied to the façade case study.

The four major items making the cost of a façade system are analysed by underlying the main differences in comparison with a standard passive curtain wall.

Engineering/Design

As introduced in paragraph 3.2, solar thermal façades require a bigger effort in terms of engineering since an energy system is implemented. The hiring of new technicians dealing with hydraulic issues and the assessment of the effects of the active façade on building energy uses and people represents a cost. This cost has to be spread on the façade system by assuming potential orders and production volumes.

By implementing a cost of 35 €/hour for each new employed person and by considering 1720 hours of working time over the year, a monthly cost of 5,017 € per person was hypothesized.

New Personnel	Yearly cost [€]
Thermal Engineering (TE)	60,200
Simulations and façade impact (Sim)	60,200
Plumber (PL)	60,200
Total cost [€]	180,600

As underlined in the above table, a new annual cost of 180,600 € should be expected within a façade building firm. Part of this cost has to be aimed to the development of the innovative façade concept.

The effort required to develop the façade system in the concept phase, hence before the material is procured and the prototype is built, was hypothesized in terms of time according to the experience gained within *Sun-RISE* project. The related cost was then calculated. Thermal engineering and simulation activities are the most time-consuming activities in this stage, especially if a new concept is developed. However, project management is also necessary to define activities and prepare documents and orders. Finally, drawings to define construction details and specifications about production and installation on site are performed.

Table 6 – Time effort to carry on a solar thermal façade from the concept to the engineering

Engineering Effort_Concept phase		
Personnel	h	workdays
TE	480	60
Sim	480	60
Project Management	240	30
Drawings and specifications	240	30
Total hours	1,440	
Total cost [€]	50,400	

Depending on the expected volume linked to this façade concept, the cost highlighted in Table 6 should be charged as Engineering/Design cost. If 500 m² of solar thermal façade are predicted over the year, a cost around 100 €/m² should be added to the standard item cost, which amounts to 100 €/m². A unitary cost of 200 €/m² might be applied for the first application. In the following applications, this cost could decrease thanks to the increased know-how, but more square meters would be necessary to pay back the employment costs.

Material Procurement

By considering the façade case study, there are components that can be tagged as standard components like the façade anchoring system, the connections to the slab, the insulated upper panel and the unitized façade frame. These items are pretty much constant and no notable variations are foreseen. Other components can affect the façade cost depending on the real needs. More specifically, the glazing system (type of glass and surface area), the shading system (it might be avoided), the insulation (material and thickness), the solar thermal collector, the water storage system, the distribution piping system, the hydraulic parts (valves, pump) and the radiant panel. Due to the bigger amount of components within solar thermal façades, the cost for material procurement might be 40 to 50% higher than the passive curtain wall façade.

Production

Production cost is also expected to rise since a plumber is necessary (direct cost) to install all the components and adaptation of the unitized façade frame is needed. For example, mullions have to be drilled to allow tubes of adjacent façade modules to be connected. Aluminium shells to locate the different components into the façade, and assuring façade requirements at the same time, are necessary. Production costs might be 50% higher than a passive curtain wall façade.

Logistics

Logistics involve the transportation of the façades to the building site and their installation. More than other active façade systems, like BIPV façades or Building Integrated Mechanical Ventilation envelope systems, solar thermal façades require on-site connections. More in detail, connections both between façade modules (connected in series) and from the façade to the centralized energy system are necessary. The economic increase for this item might be quantified in a 20 to 40% higher cost respect to a passive curtain wall façade.

During the design process of a building many obstacles and uncertainties can come out. These unforeseen aspects can be faced in two ways: by making a step back and change the design or by trying to solve issues and pursue the prefixed design. The façade case study, called *Solar Active Façade*, was first analysed in terms of components and technical costs to highlight the potential basic cost. The cost analysis of a 1.5x3.2m façade module with a 50% WWR was discussed with a façade engineer working for the company involved in the project. The list is reported in Table 7. The obtained unitary cost per square meter was used as basic cost on which applying theoretical increase factors implementing the riskiness of the investment. Assumptions regarding possible applications of the solar thermal façade as building envelope are specified in the next sub-paragraph.

Table 7 – Active Solar Façade (case study) cost analysis

ACTIVE SOLAR FAÇADE_BOLZANO			UNITARY COST [€/unit]	Quantity		Amount [€]	Notes
48.8%	MATERIAL PROCUREMENT	FAÇADE ANCHORING SYSTEM	50.0	2.0	unit	100.0	2 brackets per façade module
		SLAB CONNECTION	30.0	1.5	m	45.0	Gaskets and others
		UPPER PANEL (insulated)	250.0	0.7	m²	184.0	Opaque panel above the window
		SOLAR THERMAL COLLECTOR_ABS+GLASS	200.0	1.5	m²	300.0	Only collector
		SOLAR THERMAL COLLECTOR_EQUIPMENT	100.0	1.5	m²	150.0	Valves, connection kit, tubes, pump
		WATER STORAGE	100.0	1.2	m²	120.0	The cost was hypothesized
		RADIANT SYSTEM	120.0	1.5	m²	180.0	Market analysis
		GLAZING SYSTEM	75.0	2.4	m²	180.0	Double low-e glazing with gas
		SELECTIVE GLASS surcharge	0.0	2.4	m²	0.0	-
		SHADING SYSTEM	300.0	1	unit	300.0	Lamellae
		WALL INSULATION MATERIALS (λ 0.3-0.4)	250.0	10.0	cm	37.5	Rock mineral wool, Cellulose fiber, EPS, XPS, Fiberglass, Woodfiber, Glass wool
		UNITIZED FAÇADE FRAME	550.0	1.0	unit	550.0	Off-site works, anchoring system
16.4%	PRODUCTION		150.0	4.8	m²	720.0	-
13.1%	LOGISTICS		120.0	4.8	m²	576.0	Transport, lifting and installation and necessary connections
21.8%	ENGINEERING		200.0	4.8	m²	960.0	R&D, simulations (models), drawings, details development
	GENERAL COSTS		5%	-	%	220.0	Secretary, project management, purchasing
			FAÇADE COST [€]			4622.0	
			FAÇADE COST [€/m²]			**963.0**	

To have a comparison with a *Passive Façade* system, Table 8 shows the cost analysis of a standard unitized curtain wall system with the same dimensions and proportions between opaque and transparent part.

Table 8 – Passive Façade (curtain wall) cost analysis

PASSIVE FAÇADE_BOLZANO			UNITARY COST [€/unit]	Quantity		Amount [€]	Notes
49.6%	MATERIAL PROCUREMENT	FAÇADE ANCHORING SYSTEM	50.0	2.0	unit	100.0	2 brackets per façade module
		SLAB CONNECTION	30.0	1.5	m	45.0	Gaskets and others
		UPPER PANEL (insulated)	0.7	0.7	m²	184.0	Opaque panel above the window
		GLAZING SYSTEM	75.0	2.4	m²	180.0	Double low-e glazing with gas
		SELECTIVE GLASS surcharge	0.0	2.3	m²	0.0	-
		SHADING SYSTEM	300.0	1	unit	300.0	Lamellae
		WALL INSULATION MATERIALS (λ 0.3-0.4)	250.0	15.0	cm	56.0	Rock mineral wool, Cellulose fiber, EPS, XPS, Fiberglass, Woodfiber, Glass wool
		UNITIZED FAÇADE FRAME	550.0	1.0	unit	550.0	Off-site works, anchoring system
16.8%	PRODUCTION		100.0	4.8	m²	480.0	-
16.8%	LOGISTICS		100.0	4.8	m²	480.0	Transport, lifting and installation and necessary connections
16.8%	ENGINEERING		100.0	4.8	m²	480.0	R&D, simulations (models), drawings, details development
	GENERAL COSTS		5%	-	%	143.0	Secretary, project management, purchasing
			FAÇADE COST [€]			2998.0	
			FAÇADE COST [€/m²]			**625.0**	

As already stated, the passive curtain wall façade has a cost that can be considered fixed. Small variations mainly depend on the glazing type and insulation layer. Another façade product was considered as alternative to a standard curtain wall. This façade system was called *Active Distributive Façade* (DF) since no solar collectors are integrated and the main function is to distribute the thermal energy produced by active solar façades or the one coming from the centralized system. A thicker insulation layer was implemented. By considering a façade frame of 1.5x3.2m and 50% as Window to Wall Ratio, the system cost is 130 €/m² lower than the Solar Active Façade.

Concerning the solar thermal façade, the achieved cost does not consider potential failures of components that are integrated in the system or design errors due to software issues or inaccuracies from the designer. These aspects and others might lead to performances and costs hardly predictable, once the system is installed and operative. For this reason, the first application could demand a notably higher cost than the one obtained with the mere façade cost analysis. To take into account possible complications, a list of risks, which might be met both during the design and construction process of the façade was done. Risks are subdivided with the respective design stage as reported in Table 9. The level of involvement of the façade, together with the potential interested stakeholders, is underlined as well.

Table 9 – Risk analysis during the building design process and involvement of the façade

DESIGN STAGE	Understand where the main risks and the potential for cost saving are located in the design process of a façade system Source for the different stages: 'Defining the Architect's Basic Services' - AIA Best Practices				
	What happens in this stage?	When and how the façade is involved?		Involved figures	Affected aspects and risks to be considered
PRELIMINARY DESIGN	Concepts of the design including spatial relationships, scale, and form are illustrated to the owner for a first review	ANALYSIS OF THE CONTEXT AND PERFORMANCE STRATEGIES IDENTIFICATION	Climatic analysis Solar radiation studies Daylighting Natural ventilation strategies		**ENERGY MODEL RELIABILITY (Validated weather data, performance indicators)** **GEOMETRY CONCEPT/SHAPE and POTENTIAL FOR INSTALLATION OF SOLAR TECHNOLOGIES ON FAÇADE/ROOF** **GLAZED SURFACES: POSITION AND GLAZING SYSTEM** **THERMAL AND ELECTRIC CONSUMPTIONS** **VISUAL COMFORT, THERMAL COMFORT AND HEALTH**
			Energy regulations and codes	Designer and local consultant (if any)	**PROJECT CONFORMITY (Permit could not be issued)**
			Identify energy performance goals and priorities	Designer/Client	**INTERACTION AMONG FAÇADE PERFORMANCE INDICATORS AND PRIORITIES OF THE CLIENT**
			Local subsidies for energy measures	Designer/Cost consultant/Local consultant	**POSSIBILITY TO RECEIVE SUBSIDIES FOR ENERGY EFFICIENCY MEASURES**
			Energy consumption studies	Designer/Software developer	**IMPLEMENTATION OF BUILDING PHYSICS IN FAÇADE ENERGY MODEL**
		REVIEW WITH CLIENT	Review with the client	Designer/Client	**CLIENT'S REQUESTS** **DESIGN INITIATIVES TO BE PROPOSED**
SCHEMATIC DESIGN	This phase produces a final schematic design, to which the owner agrees after consultation and discussions with the architect. Cost are estimated	HIGH PERFORMANCE STRATEGIES USING PERFORMANCE BASED APPROACH	Integration of services and pipes	Designer	**FAÇADE MAINTAINABILITY** **FAÇADE PERFORMANCE**
			Detailed solar thermal studies	Designer	**ENERGY SYSTEM SIZE** **BUILDING GEOMETRY AND ORIENTATION** **SHADING DEVICES DESIGN**
			Energy model development	Designer/Software developer	**PERFORMANCE INDICATORS PREDICTION**
			Façade components analysis	Designer/Façade manufacturer/Product suppliers	**FAÇADE LIFE CYCLE AND COST ANALYSIS**
		REVIEW WITH CLIENT	Review with the client	Designer/Client	**LACK OF TECHNICAL DATA TO PROMOTE NEW SOLUTIONS** **CLIENT'S SATISFACTION - NEW REQUESTS**
DESIGN DEVELOPMENT	The DD phase often ends with a formal presentation to, and	HIGH PERFORMANCE STRATEGIES USING PERFORMANCE BASED APPROACH	Technology development/Choice of materials/Façade requirements/Integration criteria	Designer/Façade manufacturer/Façade consultant/Client (should require test on façade)	**FAÇADE PERFORMANCE, LCA, FINANCIAL MODEL** **ENERGY MODEL CALIBRATION** **FAÇADE MAINTENANCE PLAN**

	approval by, the owner		Façade thermal analysis	Designer/Façade manufacturer	**CONSTRUCTION DETAILS** **THERMAL BRIDGES AND CONDENSATION**
			Detailed energy model using the established building geometry	Designer/Software developer	**GAP BETWEEN PREDICTED AND EFFECTIVE PERFORMANCE INDICATORS** **ENERGY SYSTEM SIZE** **FAÇADE TECHNICAL DATA (if any)**
			Detailed economic analysis	Designer/Façade manufacturer/Façade consultant	**FAÇADE SYSTEM AFFORDABILTY**
		REVIEW WITH CLIENT	Review with the client	Designer/Client	**LACK OF TECHNICAL DATA TO PROMOTE NEW SOLUTIONS** **CLIENT'S SATISFACTION**
CONSTRUCTION DOCUMENTS	This phase results in the contractors' final estimate of project costs.	HIGH PERFORMANCE STRATEGIES USING PERFORMANCE BASED APPROACH	Update energy model based on latest documents	Designer/General contractor/Client	**FAÇADE PERFORMANCE, TECHNOLOGY AND COST** **ENERGY PLANT SIZE**
			Provide carbon - emissions analysis for all of the stages of building's life-cycle (including construction, operation and demolition)	Designer/Product suppliers/Façade manufacturer	**SUSTAINABILITY TARGETS**
		REVIEW WITH CLIENT	Review with the client	Designer/Client	**CLIENT'S SATISFACTION**
NEGOTIATION PHASE to select a bid					
CONSTRUCTION	This phase begins with the initial contract for construction and terminate when the final certificate of payment is issued.	LOGISTICS AND EXECUTION	Façade production	Façade manufacturer/Product suppliers	**QUALITY OF THE FINAL PRODUCT depending on prefabrication rate and production site**
			Façade and components transportation	Product suppliers/Planning supervisor	**QUALITY OF COMPONENTS AND MATERIALS GETTING THE BUILDING SITE**
			Façade installation	Construction company/Façade manufacturer/Product suppliers	**BUILDING PERFORMANCE (air and water infiltration, damages to building components)**
			Hydraulic connections between façades and between façade and building	Construction company/Façade manufacturer/Product suppliers	**FAÇADE PERFORMANCE** **DURABILITY OF THE FAÇADE SYSTEM**

3.4.2 The know-how increase's effect on costs

Each one of the design stages involves the building envelope with a different level of detail and efficiency in terms of decisions as for the entire building.

If proper decisions are not made at the conceptual design stage, the building will almost certainly require more costs for construction and operation (e.g. often it takes huge air conditioning equipment and much energy to compensate for poor orientation, window placement etc.). Figure 45 shows the effectiveness of decisions during the building's lifetime. The cost is not only in terms of money, but also in poorer building performance in terms of comfort. Inefficient buildings contribute significantly to both pollution and greenhouse effect. In the integrated design process, a building concept can only be developed if participants contribute their ideas and their technical knowledge very early and collectively. The concepts of energy and building equipment will not be designed complementary to the architectural design, but in a very early stage as an integral part of the building [85].

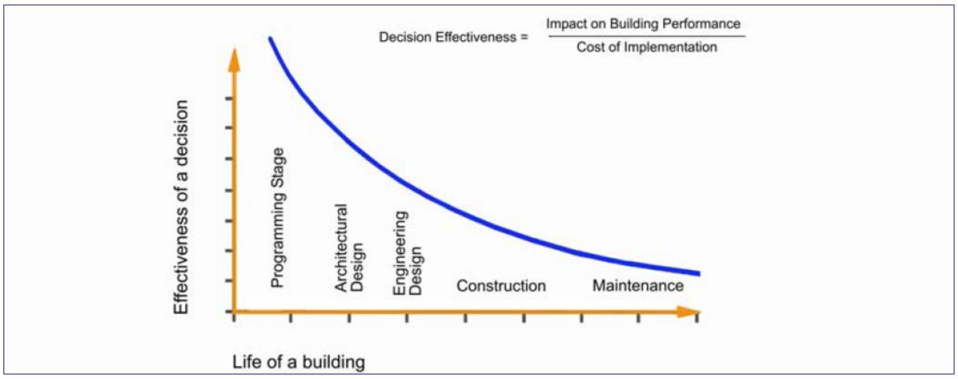


Figure 45 - Effectiveness of decisions during the building's lifetime [85]

Preliminary Design

VERY HIGH EFFECTIVENESS OF DECISIONS - HIGH COST INCREASE FACTOR

You are selling a façade system promising a certain performance. What if these performances are not met over time, when building is occupied? A gap between predicted and effective KPI would lead to an increased cost of operation. This bigger cost could be hypothetically charged to the façade system itself. First step is to assess the climate potential of the context. Building shape, fenestration ratio and potential for solar thermal installation depend strongly from this aspect. The client has to be satisfied of the proposal and the energy concept.

Schematic Design

HIGH EFFECTIVENESS OF DECISIONS - HIGH COST INCREASE FACTOR

The creation of a reliable energy model is a necessary step to size the energy system and to foresee the façade performance in terms of energy consumptions, comfort, energy production and costs. Depending on the energy system integrated in façade, maintenance costs can vary over time. A first analysis of the life cycle helps to understand the frequency of intervention. The strategy of shading control can be very important.

Design Development

MEDIUM EFFECTIVENESS OF DECISIONS - MEDIUM COST INCREASE FACTOR

The real performance of a façade system is strictly connected to the choice of the materials to be implemented in. A detailed analysis of the façade system using FEM and CFD-based software allows to assess the impact of thermal bridges and condensation risk or the efficiency of a ventilation layer. These kind of data can support the façade manufacturer to better sell a system and demonstrate the affordability in comparison with consolidated solutions. CFD analysis and measured weather data shows that energy loads are usually overestimated of about 65%.

Construction Documents

MEDIUM EFFECTIVENESS OF DECISIONS – MEDIUM to LOW COST INCREASE FACTOR

Energy model should be adjusted according to construction documents and change orders (if any). The business plan is consequently modified. Construction details and façade joints are developed in this stage. Specification for materials are here included.

Construction

LOW EFFECTIVENESS OF DECISIONS - LOW COST INCREASE FACTOR

Once the detail drawings are finalized, the façade production phase can starts. The more industrialized the final product the better the quality of the work. The building site supervisor has to be doubtless about the provenience of materials/assembled products and the status of the same. The way of installation (different workers and plumbers) can affect the actual performance of the system and this is something that cannot be easily foreseen through simulations.

The first application is a sort of demo-case: it is expected that many issues can emerge, both during the design process and the on-site assembly. Starting from the unitary cost showed in Table 7, 963 €/m², cost increase factors are applied at each stage, raising the façade cost to 1116 €/m² (+16%). The variation of the cost over the design process is shown in Table 10. Increasing factors reflect the effectiveness of the decisions. Usually the risk and profit margin applied in the construction field is between 5% and 10%. Considering the higher potential risk of active façade systems, 16% is quite realistic after having discussed it with the head of the technical office of a façade company.

Table 10 – Variation of the façade cost during the design process at the first application

APPLICATION # 1	Basic façade cost [€/m²]	963	Façade cost	% increase
	Cost increase factor		€/m²	-
PRELIMINARY DESIGN	YES	1.05	1011	105%
SCHEMATIC DESIGN	YES	1.04	1052	109%
DESIGN DEVELOPMENT	YES	1.03	1083	112%
CONSTRUCTION DOCUMENTS	YES	1.02	1105	115%
CONSTRUCTION	YES	1.01	**1116**	116%

If more applications are foreseen, it is legitimate to expect the reduction of some costs. Material procurement costs remain the same regardless the number of applications, since the used technology are standard products that do not require optimization. Production costs might decrease thanks to the improved know-how over time (less time to produce a façade module is needed). Engineering costs also decrease thanks to the improved expertise over time (less time for the façade layout and performance calculations is needed). The following tables refer to a hypothetical threefold application beside the first one.

At the second application, the basic cost of the façade is subject to a 5.5% reduction due to design and production improvements, while risk factors are not considered during the construction documents and construction stages. Table 11 reports the evolution of the cost according to the assumptions done. A 12% increase of the basic cost was estimated.

Table 11 - Variation of the façade cost during the design process at the second application

APPLICATION # 2	Basic façade cost [€/m²]	905	Façade cost	% increase
	Cost increase factor		€/m²	-
PRELIMINARY DESIGN	YES	1.05	951	105%
SCHEMATIC DESIGN	YES	1.04	989	109%
DESIGN DEVELOPMENT	YES	1.03	1018	112%
CONSTRUCTION DOCUMENTS	NO	1.02	1018	112%
CONSTRUCTION	NO	1.01	**1018**	112%

A continuous reduction of costs with increasing the number of applications was assumed. At the third application, a reduction of the risk factors was implemented, leading to a 7% cost increase with reference to the basic façade cost.

Table 12 - Variation of the façade cost during the design process at the third application

APPLICATION # 3	Basic façade cost [€/m²]	858	Façade cost	% increase
	Cost increase factor		€/m²	-
PRELIMINARY DESIGN	YES	1.03	884	103%
SCHEMATIC DESIGN	YES	1.02	901	105%
DESIGN DEVELOPMENT	YES	1.02	919	107%
CONSTRUCTION DOCUMENTS	NO	1.02	919	107%
CONSTRUCTION	NO	1.01	**919**	107%

When it comes to the fourth building application, the basic cost is reduced by almost 18% thanks to halved costs for engineering and production. A little risk is still foreseen, but uncertainties are expected to take place only in the preliminary design stage, as reported in Table 13, hence a minor cost increase factor is applied causing a final cost increased of 2%.

Table 13 - Variation of the façade cost during the design process at the fourth application

APPLICATION # 4	Basic façade cost [€/m²]	779	Façade cost	% increase
	Cost increase factor		€/m²	-
PRELIMINARY DESIGN	YES	1.02	795	102%
SCHEMATIC DESIGN	NO	1.02	795	102%
DESIGN DEVELOPMENT	NO	1.02	795	102%
CONSTRUCTION DOCUMENTS	NO	1.02	795	102%
CONSTRUCTION	NO	1.01	**795**	102%

The final cost at each hypothesized application is reported in Table 14. Assuming that all of the hypotheses are true, an increasing cost decrease rate might be actualized over time. Certainly the final cost can not always be reduced. Once the engineering and the production costs are minimized, the potential for cost reduction could be associated only to mass production and use of cheaper materials.

Table 14 – Comparison among potential turn-key façade costs

	Turn-key façade cost [€/m²]	Cost decrease rate
APPLICATION # 1	1116	-
APPLICATION # 2	1018	8.8%
APPLICATION # 3	919	9.7%
APPLICATION # 4	795	13.6%

The façade cost analysis and the possible evolution of the turnkey cost over time linked to several applications was illustrated. Despite the potential reduction of the investment, this remain of some significance. For this reason, support schemes are necessary to expand the market.

Some years ago, when the market was blooming, it was already stressed the need for clear political signals that would enable large investment in the sector, in particular support schemes and long-term incentives. The solar-thermal sector cannot benefit from schemes such as feed-in tariffs, unless we start to adopt heating networks in widespread way.

Zhang et al. [28] emphasized that the implementation of the Active Solar Thermal Façade systems is much different from a 'business as usual' component. Consequently, it is worth to treat the business related problems as an investment project to make it financially attractive. For example, the method determining the cost saving from the tariffs of heating energy is a market-based approach to assess the energy cost savings and associated benefit to energy management, but it might be not suited for these technologies. Koene [86] studied a business model including a few critical factors: (1) instalments + interest to return the investment over a 15 year duration; (2) operational&maintenance costs (O&M); (3) fixed energy service charge in case that an E.S.Co. provides the energy services; (4) energy costs minus revenues from renewable electricity generation, and (5) rent. A list of costs of all the elements in all renovations was entered into the business model. The costs for the novel ASTFs were in the range 450 to 550 €/m² per façade including 20% VAT and labor cost for installation. A sensitivity analysis using the Monte Carlo model was then undertaken by considering the variation of a number of parameters, including the investment cost and discount rate. From this study, it was found that the main parameters that determine a positive outcome of the business cases were the rent and the investment cost.

By the way, in office building the priority is renting out as much floor surface area as possible. Open spaces allow to get more floor surface area to be sold, since internal walls are no more needed. Another point concerns the interest of real estates in selling building with active façades. Very few people care about the energy plant. Companies renting office buildings, or simply floors, just want a standard energy system and both owners and tenants want low maintenance costs. Solar thermal façades might just move some of the maintenance towards the envelope.

As reported by ESTTP experts in [1], many investors have come to realize over recent years that electricity generation from photovoltaic, wind and bio energy was strongly supported by feed-in tariffs, which made their investments profitable. In contrast, support for solar thermal energy has usually been only through a small incentive or stimulus, which has not helped close the competition gap with fossil fuels. In addition, the risk from the incidence of energy price on the competitiveness of the solar thermal technology is borne by the investor, whereas with the feed-in tariff scheme it is passed on to the electricity consumer. Therefore, many investors prefer to invest in renewable electricity generation. Another factor has not be neglected: fossil fuel energy price costs are decreasing, and this goes against every forecast. According to Eurostat data, natural gas and electricity costs to domestic consumers in the European Union range between 2.76 to 11.65 Eurocents/kWh for natural gas and between 8.74 to 29.75 €cent/kWh for electricity.

3.4.3 The revenue account for solar thermal façades

The movement of energy systems towards the envelope of a building is a concept that some façade builders are considering, but without implementation as far as the author is aware. In a world where the available time to build buildings is increasingly short, the development of solutions creating the opportunity to spend as little time as possible on the building site could be the favored ones. It would mean getting buildings with a higher value in comparison to those realized with standard solutions. A higher income for the building owner might be predicted. The use of service-integrated façade systems can lead to a higher monthly payment to rent the office building. Finally, the contribution/subsidy from governments for RES integration is something that should be foreseen as well, but avoiding the errors made in some markets like the photovoltaic one. These financial sources should be calculated only on the delta cost payed to integrate renewable energy sources into façade.

An important aspect to be implemented in the evaluation of solar thermal façades are the avoided costs due to functions fulfilled by the façade. Indeed, some energy systems are no more necessary. Depending on the integrated technologies, less on-site works can be needed (e.g. fan coil units substituted by an energy distribution system integrated into the façade), energy needs can be reduced thanks to higher thermal mass capacity, the energy distribution piping design may be simplified. On the other side, extra costs have to be quantified. The integrated technology itself is an extra-cost in comparison to a standard passive façade system. New energy fluxes and needs are due to the active façade system. A bigger cooling load is foreseen and investigated through energy simulation studies.

Extra costs are closely related to the new components integrated into façade, the maintenance of the active components and the energy demanded for the pump operation and for the potential bigger cooling load due to the transfer of heat through the façade when the water storage is fully charged.

Besides the cash flows due to avoided and extra costs, strategies and support schemes can be considered to pay the initial extra cost back within a shortest period as possible. Two possible strategies supporting the investment can be implemented: higher monthly rent defining a higher building value and government subsidies. The public subsidy for RES integration is expressed as percentage of the façade extra-cost, while the rent increase is obtained as difference between a standard monthly cost per square meter and a new proposed rent.

Criteria to decide the minimum payback period are manifold, but two constraints might be stricter than others: the warranty period of the solar thermal system integrated into the façade and the durability of the façade system as a whole. Concerning the warranty, solar thermal collectors are usually guaranteed for a 10-years period, hence it would be reasonable pay back the investment of the solar thermal collector within that time. Regarding the durability, it is not easy to assess the stability of the entire system. The durability of a product is equal to lower durability of the components making up the product. The frame of unitized curtain wall façade can guarantee the stability of the system for a long time, maybe also 50 years, which is the typical lifetime span of a building. However, insulating glazing units, gaskets and other components require the substitution within shorter times. According to the lifetime span of the façade components listed in paragraph 3.3, 15 years might be a rational period to pay back the extra-investment.

Every investment pays back in a proper way, especially when solar active systems are involved. Indeed, depending on the location, the façade orientation, the load match between energy production and energy need, the return of investment is subject to variations. The proposed methodology to assess the convenience of solar façades starts from an analysis of single office rooms configured by combining different active façade modules and by quantifying the extra-cost in comparison with the same office room having a passive façade and fan-coil units to climate the space. The energy model used to assess the energy performance of the different configurations is explained in detail in chapter 4.

Several features are necessary to model the façade concept. First of all, the active façade system has to be geometrically identified in terms of height, width, Window to Wall Ratio and solar thermal collectors' size. Office room dimensions are necessary to apply the methodology at the single zone scale. An office room of 6 m depth and 4.5 m width was implemented. Many scenarios can be defined by configuring the façade in terms of number of active and passive façade modules. An energy model is also essential to get other information necessary to assess the energy match and the operation time of the envelope integrated system.

3.5 Active envelopes and façade construction companies

Developing and engineering new products following an experimental methodology is part of the readiness level pyramid. However, reaching the highest technology readiness level also depends on the real interest and need of solutions on the market. To understand the awareness of façade construction companies about the façade as integral part of the building energy system, a questionnaire was sent to several manufacturers of the sector.

Twelve questions were addressed to five façade companies, but only two accepted to be interviewed. The questions cover different disciplines, from technology to responsibilities in case of failure, to costs and internal organization. Here are the questions:

1. *Do you have sufficient skills and will inside your company to promote innovative façade solutions integrating Solar Thermal systems?*
2. *What do you think about moving the mechanical systems (ducts, distribution and installation) towards the façade?*
3. *Would you sell your product by including a maintenance service over time?*
4. *Are you usually involved in the very early design stage of buildings and façades?*
5. *Which are in your opinion the key factors to be communicated to the decision makers to better sell building integrated façade systems?*
6. *Since the curtain wall systems have reached a state of maturity, do you see any potential for cost reduction within the façade value chain?*
7. *Which are the main risks and complaints you usually run into (generally speaking about façades)?*
8. *How do you consider sustainability aspects? From the conceptual design to the building end of life*
9. *How much time do you usually have between the delivery of drawings from architects to the elaboration of façade details?*
10. *Where is located the business core of a façade builder? (R&D, Design, Material, Production, Transport, Assembly, Operation of building, End of life)*
11. *Which new risks do you foresee in solar façades?*
12. *What is the actual cost of a façade system over time?*

Both the interviewees are the responsible for the R&D department. The answers were summarized and divided by topics touched with the questions.

Innovation during the design process

One interviewee said nowadays investments in Research and Development within façade companies is not right balanced. Development takes more money and time, while Research concerns a lesser extent. Both the companies are investing time and money on the active façade topic since they want to be ready, when it will be the time, to face issues linked to solar façades. Regarding the available time to develop new ideas, a modification in the tendering process (at least in Italy) is a necessary step. They should foresee the payment for the construction of mock-ups even for those who do not win the tender. At least an expertise would be developed and façade builders would increase expertise over time. Unfortunately, there is no time to study or propose other solutions. Times are very tight and everything has to be scheduled perfectly (design, materials order, production).

70% of times, the façade company involvement in the design process starts with the executive design stage; otherwise, if involved earlier, during the design development. When it comes to complex façade systems, façade value engineering and mock-up developments become crucial, hence the involvement of façade builders becomes paramount.

Active and Flexible Façades

The integration of energy systems into façade makes sense only if a direct advantage from free energy can be derived. Furthermore, the comfort thematic has to be managed. However, it is noteworthy to think and to design façade and building energy system as a unique entity: understanding the real size of the centralized system as function of decentralized systems integrated into the façade and taking into account the real internal gains and the use of the building. It is likely that management costs are reduced since single rooms can be controlled with decentralized systems. Less space for ducts in the dropped ceiling might be necessary and space could be saved others things being equal.

Design customization is something that should be allowed to architects and a façade configurator might be the solution to assess façade composition and the energy system layout in a first stage. There are examples of façade products, which did not find the marketing they expected for two main reasons: low flexibility in design and not clear structure in supplying and responsibilities. Designers should have a tool helping them to configure the whole façade with active and dummy elements. Since architects care about the aesthetic and the appearance of the building more than anything else, it is paramount offering a flexibility of the system, otherwise you lose immediately.

Internal skills

In addition to the current personnel dealing with manufacturing and assembly of façade components like aluminium profiles, gaskets, glazing systems, we would need two more figures. One facing thermal engineering in terms of simulations and plant layout design, which might be a researcher, and another one assessing the impact of high temperatures systems as it would occur with these façades in order to evaluate risks for both thermal expansion of façade components and for user's comfort. If dynamic systems are integrated into façade the energy modelling will become always more important; for this reason someone skilled should be hired but only after a period of knowledge acquisition through external consultants and specialized studios. It is important to understand whether the skilled person is necessary for the entire year or not. The same thing happened for the statics matter within one of the two companies: at the very beginning, nobody dealt with static calculations but only façade construction, but after many years they decided to develop internal skilled people dealing with the subject and for several years they have been designing the static of the façade and the building structure.

Risks and costs

It is hard to investigate risks and to say how and if they (of any typology) affect/define the final cost of the façade. Complexity of the building site, design of the façade system and shape of the envelope already determine high costs. When it comes to building systems integration, there are delta costs to be examined, mainly related to: engineering (modelling, simulations, and prediction analysis), materials, production, installation, maintenance. New financial models are necessary. Investments should favour only the own energy consumption.

Reducing costs in the façade production chain is rather hard nowadays. You can reduce production costs by moving this activity in other countries like China, Vietnam or India, where manpower is cheaper. However, this makes sense only when façade surface amounts to more than 15,000 m² and is based on standard solutions. The potential to reduce costs is also connected to the materials and the entity of the work, of course. Nowadays is very common in curtain wall façades the installation of triple glazing systems with selective films to comply architectural requirements. This represents a higher cost in comparison to other glazing systems and the higher weight (compared to a double glazing system) implicates the use of other aluminium profiles. The higher the number of equal pieces and the higher is the level of automatization, hence the higher is the reduction of costs for material procurement and production.

The introduction of unfamiliar components, like solar thermal collectors, into façade concepts can easily make the façade 40% more expensive than consolidated envelope technologies, based on one interviewee's experience. This is due to the lack of a specific know-how applied to façade systems. The cost analysis carried out in the previous paragraph showed that the total cost of investment of the solar thermal façade is 60% higher, but the analysis also demonstrated that is not fair comparing just the initial cost related to the façade if active components are integrated. Indeed, the energy system has to be contemplated as well.

Responsibilities

The interviewees agreed on ensuring to the client the foreseen productivity of the system, but they are aware of the risks they can run into like the loss of durability of materials due to high operation temperatures. Since responsibilities and maintenance recurrence change, different warranties (in comparison with standard façade systems) might be necessary. New certifications and related procedures for façade builders are needed to understand who is responsible and to which extent. Two main opposite strategies can be adopted to develop façade systems and manage risks. One is creating a spin-off within the façade company dealing only with active façades; in this case the façade builder controls each step and interfaces are all inside the same place, then it assumes all the responsibilities. The other way to proceed is keeping the interfaces separated (façade builder, designer, thermal engineer, energy modeler) by risking long development times and difficulties in communication. A middle way situation should be found.

During the building lifespan, a maintenance service is foreseen most of the times. In order to manage medium-long term risks, an agreement with expert system suppliers who are then responsible for the operation of the components they supplied is done. Usually a maintenance service is offered by paying an annual fee.

Concluding, the third chapter clarified the implications of introducing solar façades (and active façade concepts in general) within the organization of companies dealing with curtain wall envelope systems. The costs involved for developing, producing and spreading a solar thermal façade were analysed. The façade case study arose thoughts to solve installation and operation and maintenance issues. Knowledge enhancement by means of applications is needed to reduce the initial investment. The building design process was assessed touching the stages where the façade is involved. Current certifications and regulations are not ready for stimulating a market of active façade systems, but demonstrating the competitiveness of solar façades is deserved and research can be really supportive in this.

Chapter 4

4 Solar thermal façades: assessing the energy performance of a façade concept

Before installing every solar energy system, an analysis of the potential for energy production is necessary. There are tools allowing designers to assess this potential but most of these consider only standard roof applications, while façade solutions and integrated products are not contemplated. First two paragraphs explain the importance and the difficulty of modelling and simulating solar façade concepts. Examples show the potential of these analyses, when conducted in the early design process. The energy performance of the solar thermal façade case study is evaluated through FEM thermal analyses and the component-based software TRNSYS, which was used to identify several solutions in terms of façade configuration and climate to populate the results emerging from the FAST-IN tool database. Limitations of the models are highlighted. Finally, the experimental study carried out by means of tests to characterize the façade thermal performance is described. Values measured from test activities were used to validate the FEM model.

Keywords: energy modelling and simulation; façade thermal analysis; façade prototype

4.1 Assessing the potential for solar energy

The design of building envelopes should consider the influence of the outdoor environment on the their performance, but also the potential influence of the façade on the outdoor microclimate and comfort. Building Integrated Solar Thermal (BIST) façade products differ one from the other for optical and thermal properties determining how much solar radiation is absorbed or reflected back to the outdoor environment. Due to these properties, solar façades can achieve high surface temperatures and affect the microclimate close to them. On the other side, the environment around a façade has an effect. Indeed, mountains, buildings, trees close to the designed building have an impact on the energy performance of the façade. A study for the assessment of the solar thermal potential on façade in the Italian city of Bolzano was carried out by using the software Skelion. The study shows that vertical installations can really make sense and should not be neglected in the early design stage.

Several researches have assessed the performance of Building Integrated Solar Technologies into façade in comparison with standard systems installed on the roof. Main outcomes have been the advantages linked to the integration as the lower heat losses from the walls and the bigger difficulty in predicting the real performance due to modeling uncertainties and major influence of shading elements like surrounding buildings and trees or mountains. Another critical aspect is the use of weather data files obtained with measurements of solar radiation in open fields. Since the performance and the payback time of solar thermal collectors is in close relation with the amount of solar radiation hitting their surface during the year (solar yield), the availability of reliable weather data taking into account the orography and the presence of other buildings is crucial. The performance of STCs integrated into façade is also affected by the amount of wind running onto the surface; indeed, heat losses on the front surface of STCs depend on the convection occurring on it. The wind force magnitude measured in open fields is by far bigger than the one occurring in presence of buildings. Furthermore, wind velocity at the bottom of a wall is one third the speed at the roof height. These aspects are crucial in assessing the efficiency of solar active technologies.

Solar thermal flat plate collectors are made of a metal box case, a dark colored absorber layer and glass. STCs developers want to ensure the highest performance as possible. To do this, most of the solar radiation should pass through the glazing system to reach the absorber, which usually is a selective surface. Reflection issues linked to solar thermal collectors were not observed in the literature, but there are some interesting cases with no active technologies integrated, where the façade was designed by not thinking to the response of the building shape and the materials. Eye catching cases are:

- *the 20 Fenchurch Street skyscraper in London, which acts as a concave mirror and focuses light onto the streets to the south reaching temperatures between 91°C and 117°C in some spots [87] when the sun shines directly onto the building;*
- *the Vdara Hotel in Las Vegas, where the south façade is a collector and bouncer of sun rays, directed to the hotel's swimming pool leading to users' discomfort [88], [89];*
- *the Walt Disney Concert Hall in Los Angeles, designed with highly polished mirror-like panels with concave sections, leading to some residents of the neighboring condominiums suffering glare caused by sunlight that was reflected off these surfaces and concentrated in a manner similar to a parabolic mirror [90].*

These three cases show that solar reflection can be very dangerous due to the concentration of sunrays. Nearby buildings can become unbearably warm, causing higher air-conditioning costs. Reflected sunrays can create hot spots on adjacent sidewalks and can increase the risk of traffic accidents due to blinding sunlight reflected from the polished surfaces.

Possible interactions between solar thermal façades, its surrounding and climate

Simplified models do not consider many environmental factors affecting the real performance of STCs. Solar collectors are affected by many variables including rate of incident solar radiation, fraction of diffuse solar irradiance, air temperatures surrounding the collector, the rate of exchange of long-wave thermal radiation, fluid inlet temperature, coolant's mass flow rate and collector slope. Once STCs are installed, they are subject to many outdoor phenomena: solar radiation ranging from 0 to 1,200 W/m²; ambient temperature from -30 to +35°C; effective sky temperature which can be 30 K colder than ambient temperature; wind speed ranging from 0 to 15 m/s [68].

In the past, it was common practice assuming that collector efficiency was only function of the three parameters used in the formula $(T_{pm}-T_a)/G_T$, where: T_{pm} is the Mean absorber plate temperature of the fluid; T_a ambient temperature; G_T solar radiation. The same value of $(T_{pm}-T_a)/G_T$ can be obtained by varying the three parameters, but only later it was noticed that variations in the rate of heat loss from flat plate collectors occur for the same value. Flat plate collectors' efficiency is strongly dependent on the top heat loss coefficient, which in turn depends on ambient environmental conditions. Performance is also function of the technology and heat removal process. For example, unglazed solar collectors are more sensitive to wind and atmospheric radiation effects.

Thermal losses from the collector consist of conduction losses through the back and the edge of the collector to the surrounding environment, and conduction, convection and radiation losses through the front of the collector. For most of the collectors, the heat transfer through the front cover is considered big compared to other losses. Hence, back and edge losses are neglected and the total heat loss coefficient (U_T) is approximated to the value of the heat loss coefficient at the top (U_{top}). Heat loss through the top of the STC is the sum of convection and radiation heat transfer. A small amount of the heat loss is due to long-wave radiation transmitted from the absorber to the atmosphere through the glass cover. The energy transferred from absorber to the cover is lost to atmosphere by convection to the ambient air. This phenomenon is enhanced by the wind. Another part is lost by radiation exchange from the cover to the sky and the surroundings.

The presence of a selective layer on the absorber is significant. Many collectors are manufactured with non-selective absorbers (ε_p=0.95) increasing the radiative heat transfer rate due to exchange between the absorber surface and glazing. Variations of U_{top} become more significant as T_{pm} and T_a increase. The heat transfer may be that of natural convection if the wind velocity is very low. As the wind speed increases, natural convection is dominated by forced convection, increasing h_w. The relationship proposed by McAdams, function of the wind speed *v*, is assumed to give reasonable estimates of this parameter.

$$h_w = 5.7 + 3.8 \cdot v$$

The higher the value of h_w, the higher is the heat loss coefficient.

Another crucial factor determining the performance of STCs is the sky temperature. To evaluate the radiation exchange between the cover of a solar collector and the sky, the sky can be assumed as a blackbody at an effective sky temperature T_s. When there are clear days and nights the effective sky temperature may be significantly lower than ambient temperature. This value mainly depends on the air temperature and the portion of the sky the collector sees. Giovanardi et al. [91] assessed the cooling potential of façade-integrated unglazed solar thermal collectors (USTC) thanks to the heat exchange with the sky. The USTC is integrated in a cassette system to be installed on a vertical substructure (Figure 46). The unglazed metal solar collector was identified as an active surface to reduce both the heating and cooling space demand in buildings. In winter sunny days, the heat produced by the vertical UST collector is transferred to a wall radiant serpentine located between insulation and the masonry, which releases the heat to the masonry making the internal wall surface warmer than the indoor air. During the summer nights, the system behavior is inverted and the solar façade actively contributes to reduce inside temperature, being the temperature of the UST collector higher than the sky temperature, and so being able to reject heat. The radiative unit, coupled in a closed water loop with the collector, intercepts the heat stored inside the building and inside the massive wall, and rejects the heat to the external ambient. The summer night cooling potential of the active solar façade was evaluated for a south oriented façade of a residential room in Rome. With respect to the same zone without an active system integrated in façade, both the surface and the zone temperature are lower. Even though the difference between zone and wall surface temperature is minimal (between 0.5 and 1°C depending on the wall material, insulation thickness and the pipe spacing), a cooling effect occurs: part of the heat inside the room is transferred outside through the façade system. The maximum cooling effect achieved during the summer season is around 275 W for a 24-m² floor surface area room.

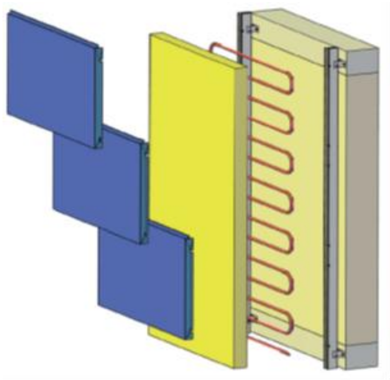


Figure 46 - Active solar façade system components: solar cassette integrating UST collectors (blue), insulation layer (yellow), radiant wall system (red), aluminum substructure and the existing masonry structure [91]

The solar potential linked to a specific building or to a cluster of buildings is obviously function of the surroundings. The real solar potential of solar technologies integrated into façade is worse than standard roof installations. Indeed, more obstructions can be present between sunrays and the vertical surface to be evaluated. Many tools have been developed recently to assess the solar potential. The need of these tools originated mainly from the Photovoltaic integration case. Some of these are just research-based tools, while others have become commercial instruments. These tools can really help decision makers to evaluate the best solutions for installation of solar technologies. Usually these resources originate from the assessment of photovoltaic energy production, which is easier to be quantified in terms of cost-benefit. Several tools are listed on the website *Solaripedia* (http://www.solaripedia.com/184/tools.html). Here follows a short list of instruments:

- *Skelion (http://www.skelion.com/): this is a plug-in for SketchUp allowing to take into account the original orography of the place where the building is located and to calculate the shading rate factor (the percentage of sun exposure time when the surface is not shaded). The tool has been created to design solar thermal or solar photovoltaic installations starting from a 3D model, using Sketchup and Google Earth to import the surroundings. Skelion is suitable for roof and façade installations. Ground-mounted power plants can be also designed [92].*
- *SolarSystem Mapdwell (https://www.mapdwell.com/en/solar): open, online rooftop-solar remote assessment tool that reveals the solar potential of building rooftops through state-of-the-art, hyper-precise, advanced technology developed by Massachusetts Institute of Technology (M.I.T.). Solar System empowers users with a comprehensive cost-benefit analysis through its open, intuitive, interactive platform. Unfortunately the tool was developed only for some urban areas of the U.S. and Chile, and is suitable for roofs [93].*
- *SEES-model (http://gvc.gu.se/english/research/climate/urban-climate/software/sees): the Solar Energy from Existing Structures (SEES) simulates spatial variations of potential photovoltaic energy production on roof structures in urban areas. The model is available through a graphical user-friendly interface. The model is suitable for roofs [94].*

Existing tools to assess the solar potential are not capable to quantify the effect of all the atmospheric factors on the collector's heat losses. Models that are more sophisticated are needed. These can be found in software like *TRNSYS* and *EnergyPlus*. Still the coupling of some physics is not yet implemented like those occurring in BIST products. Indeed, only standard STC models have been developed.

The integration into façade of STCs could even reduce the risk of sunlight reflection since a good part is absorbed, but the problem might be the surface temperature achieved. This aspect can worsen the Urban Heat Island phenomena.

Unlike roof installations, the performance of active façades can be improved with the sunlight reflected from both the ground and close vertical surfaces. As far as the author is aware, there are not tools developed to investigate this aspect, but there are software implementing reflection models that might be used to assess the potential benefit from reflection on STC performance.

These aspects go under the name *Inter-Building Effects* and depend on the climate context. Since building indoor environment and consumptions depend mainly from the envelope performance, which in turn is influenced by outdoor conditions, these effects should be taken into account when the solar potential for façades and roofs is assessed.

Pisello et al. [95] proposed a method for evaluating a building's energy performance by enlarging the assessment perspective from a single building to a network of buildings. The IBE analysis and the specific proposed methodology revealed energy requirement modeling inaccuracies both in summer and in winter. Two climate contexts were compared: Minneapolis, MN, and Miami, FL. Substantial energy over-estimation amounts were found, meaning that less energy is needed than predicted due to the IBE. This is largely due to mutual shading across the network of buildings. Those over-estimation amounts were up to 58% for Miami and up to 37% for Minneapolis. At the same time, energy under-estimation up to 32% was observed for the residential block modeled during cooler weather months in Minneapolis. EnergyPlus was used as modeling environment to model a real urban block.

He et al. [96] developed a 3D CAD-based design tool to reproduce the spatial forms of buildings and constructed surface materials, capable of quantifying the influences of outdoor configurations and surface materials on both indoor and outdoor environments. It was noticed that the presence of trees, in addition to the indoor cooling energy saving effect, have a thermal improvement effect on outdoor thermal environment.

These studies did not implement any solar technology potential installation. Kanters et al. [97] evaluated the solar energy potential of four common city block layouts in Sweden. Surfaces on the building envelope -roof and façade- were considered suitable when they have a solar yield higher than 650 kWh/m²a. The solar energy potential of the city blocks was simulated with DIVA-for-Rhino and was expressed as electricity and heating energy demand coverage. They carried out a sensitivity analysis on density and rotation of the blocks to make easier the comparison of alternative scenarios during the early design stage. Assumptions were necessary (proportion between PV and ST area, efficiencies, energy demand to be covered). No considerations about overheating and high-temperatures risks were mentioned.

An example of solar potential study, using *Skelion*, finalized to assess the potential for thermal energy production by installing solar thermal collectors on façade is showed in the followings.

<u>Methodology</u>

Within the European Project FP7 Sinfonia [98], several retrofit scenarios for a residential case study implementing active technologies were hypothesized and assessed in order to be compared with other solutions like simple external thermal insulation. Energy retrofit goals were: 50% coverage of DHW demand, reduced space heating demand partially covered with renewable energy sources, PV plant power capacity of 27 kWp. Concerning the solar thermal DHW load covering potential, different scenarios of technologies and roof/façade opaque area usage were compared.

Figure 47 – Building case study_North-West façade (left) and South-East façade close to the mountain (right)

The 4-storey building is located in Bolzano and is oriented in the south-west/north-east direction. The building complex includes two apartment blocks (36 flats each), which will be retrofitted. The whole complex has an average 21% window to wall ratio. Unfortunately, a good part of opaque surface area is exposed to north-west, but still a lot of façade surface area can be potentially covered with active technologies. Solar radiation was calculated for almost all the façade surfaces but only the south-east and south-west fronts were considered for the solar thermal potential assessment.

Two main steps were followed to investigate the solar thermal potential for the building case study:

1. *The solar potential on façade and roof was estimated to localize the best position (orientation and tilt angle) for the installation of solar thermal collectors, considering both façades and roof, to achieve the post renovation goal.*
2. *The needed STC surface area to cover a specific part of DHW was calculated, considering also the overheating risk.*

<u>Solar potential to identify areas of installation</u>

Since the building is located close to a mountain (Figure 47), the surrounding is expected to affect strongly the technological implementation into façade for energy production purposes. A 3D model is necessary to assess the solar potential and to identify the surfaces where it makes sense install STCs on. *Skelion* was used to evaluate this potential. The instrument allows the user to implement shadings due to the orographic context, near buildings and other objects (such as trees). The process is very simple. First, the context area of interest was imported from Google Maps and the local coordinates system and the map were aligned with respect to the north direction. Building case study is highlighted in Figure 48.

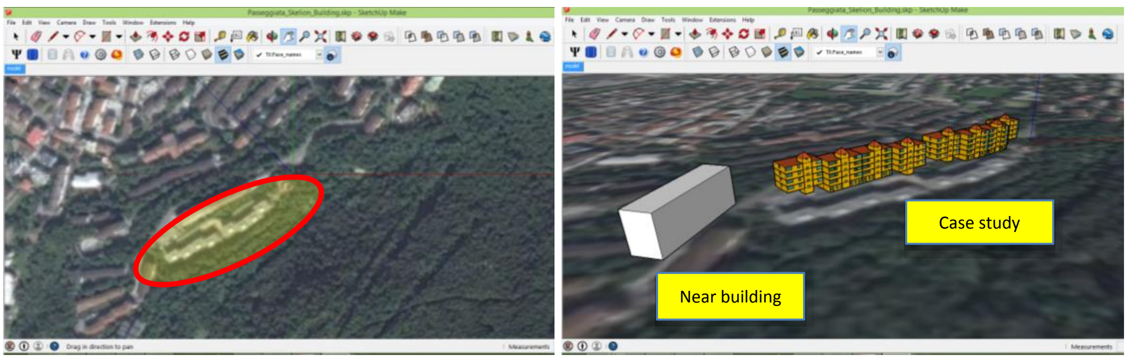


Figure 48 – Building case study from Google Maps (left), imported in SketchUp through Skelion_SketchUp model (right)

A SketchUp model of the building complex and the close apartment block, which can affect the solar irradiation on façade, was created as showed in Figure 49. Finally, global solar irradiance and shading rate factor were calculated.

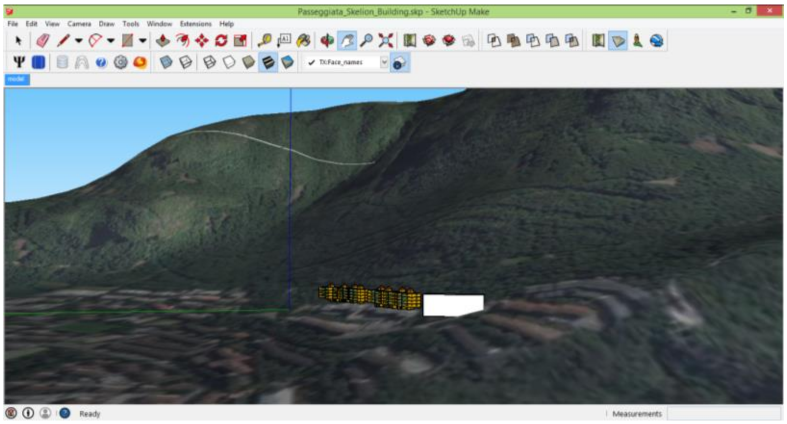


Figure 49 - Building case study with orography

The average global solar irradiance for each building front is showed in Figure 50 with dark colors, while façade surface area is highlighted with light colors. NW and NE façades are not considered as the available solar energy is in the range of 360-400 kWh/m²y, more than 50% less than the SW façade. The minor solar yield of the NW and NE façades would results in a less cost-effective investment because of the need to install higher amount of solar devices. For these reasons, only SW and SE façades have been investigated more in detail: Figure 51 shows the available façade opaque surface area and the related solar irradiance for every storey. South-west façade is well sunlit with a decreasing gradient of solar available energy from the fourth floor to the first one due to the presence of another building close to the façade. Nevertheless, the available opaque surface area is limited.

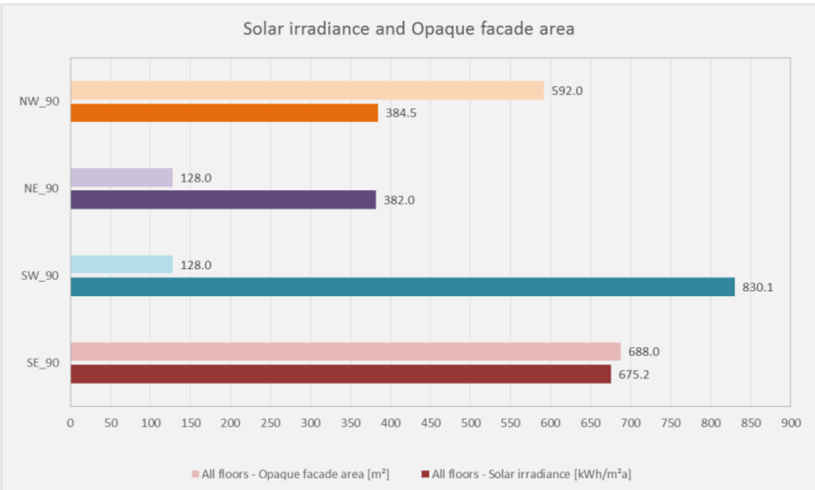


Figure 50 - Solar irradiance (dark colour bars) and available opaque façade (light colour bars) surface area depending on orientation and shading of the surroundings

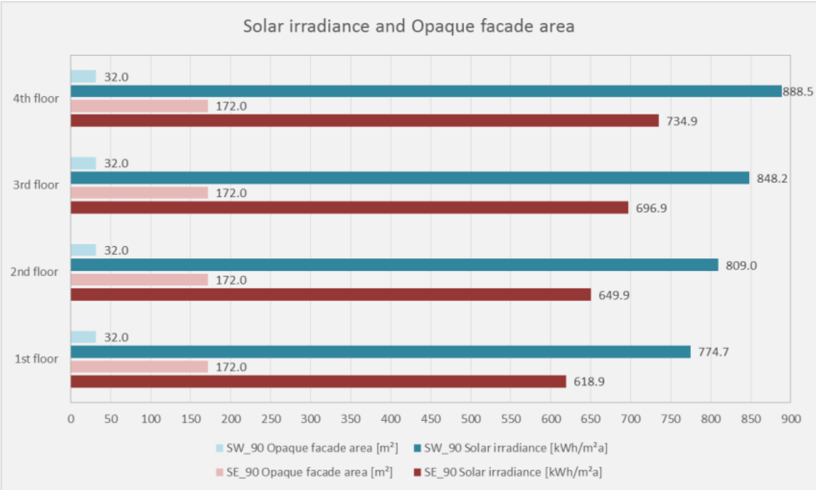


Figure 51 - Solar irradiance and available opaque façade surface area depending on orientation and building floor (only SW and SE fronts)

Concerning the solar potential on the roof, the maximum solar energy is available when the receiver has 34° tilt angle. In conclusion, three locations were identified for the installation of solar thermal collectors: south-east façade, south-west façade and roof with south exposure and 34° tilt angle.

<u>Solar thermal potential for the preliminary design of the system</u>

After having identified the best locations for installation of STCs, the potential production of thermal energy to cover Domestic Hot Water was calculated. The methodology involved the use of the software *TRNSYS* and *Meteonorm*. The procedure included the:

- *Creation of weather files in terms of temperature and solar incident radiation with Meteonorm, considering the user-defined horizon with mountains and the near building;*
- *Calculation of total incident solar radiation on the desired surfaces through TRNSYS Type 15-6;*

Hourly trends of solar power are well modelled including shading of the mountain and of other surrounding as clear from Figure 52: for the south-west facing (45°) façade the incident solar radiation is cut down to the level of the diffuse radiation (almost as for the south-east surface).

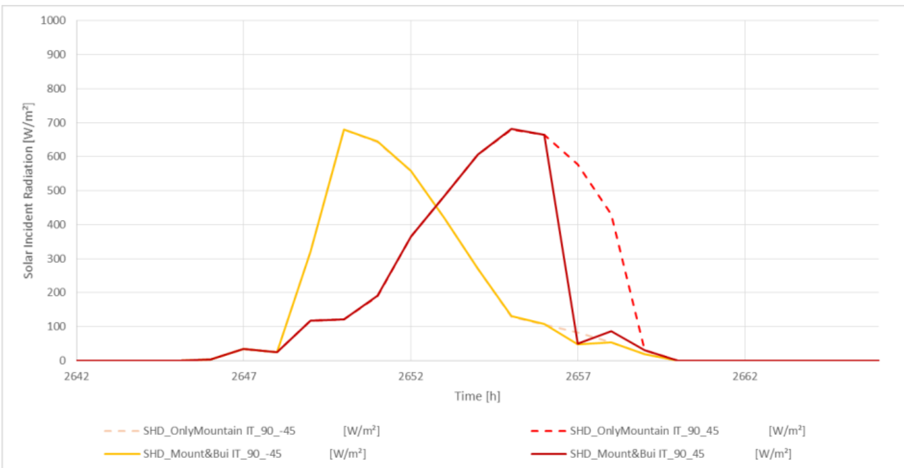


Figure 52 - Solar radiation (incident+diffuse) trends for a typical spring day for two façade orientations. Note:-45 refers to south-east façade; 45 refers to south-west.

- *Application of the ST efficiency quadratic relation to get the ST output thermal power, assuming a constant collector temperature over the year as reported in [99]. A constant collector temperature T_m of 50°C was considered in the following equation as suggested in [100]. Solar powers output from the solar thermal collector is:*

$$P = A \cdot (\eta_0 \cdot G - a_1 \cdot (T_m - T_a) - a_2 \cdot (T_m - T_a)^2)$$

where A is the receiver surface, G is the impinging solar radiation in W/m², T_a is the outdoor ambient temperature and η_0, a_1, a_2 are the solar thermal collector efficiency parameters.

- *Implementation of the storage by treating it in the calculation as a node with one power input (ST) and one power output (DHW demand): hence, the average storage temperature is calculated hourly knowing the load profile and the solar radiation hitting the façade. The storage temperature (even if averaged on the storage volume) is useful to assess the risk of overheating of the hydraulic solar network. Storage dimension is sized considering a constant specific water volume per collector area (50 l/m²). A radiation set point of 200 W/m² controls the solar thermal production.*
- *Calculation of DHW energy demand from the UNI TS 11300 data on volumetric needed mass flow rate and nominal water delta T. This energy is then converted in hourly power assuming a load profile with homogeneous volume demand in the occupied hours. Yearly DHW energy demand is around 19 kWh/m²y, in line with the retrofit goal for the case study.*

Results and discussion

Three different installation locations (façade SW, façade SE and roof S 34° tilted) were set, trying to design the ST system for reaching the 50% of DHW yearly energy demand. Four different solar thermal collectors available on the market were compared. Features are reported in Table 15. SW and SE gross surfaces were considered on all four floors. Roof area is referred to the horizontal surface without the stairwell towers. For each scenario, the not usable surface is also indicated: not usable refers to the surfaces with high shading (10% higher than the average for that orientation). The needed gross surface of ST per each scenario is below the maximum available envelope surface apart from the SW façade, where the surrounding shading causes a reduced energy yield for which a higher façade area would be needed to achieve the goal depending on the collector technology. The case of enhanced ST flat plate collector (ST_2) is showed in Figure 53.

Table 15 – Main features of the four solar thermal collectors compared in the study

		Flat Plate (ST_1)	**Flat Plate (ST_2)**	**Vacuum Tube (ST_3)**	**Vacuum Tube (ST_4)**
eta	[-]	0.78	0.832	0.777	0.792
a1	[W/m²K]	4.20	3.92	1.39	1.62
a2	[W/m²K²]	0.02	0.0126	0.0082	0.0021
Aabsorption	[m²/coll]	2.32	2.065	3.019	1.114
Agross	[m²/coll]	2.51	2.376	4.343	1.588
Aaperture	[m²/coll]	2.33	2.036	3.222	1.069

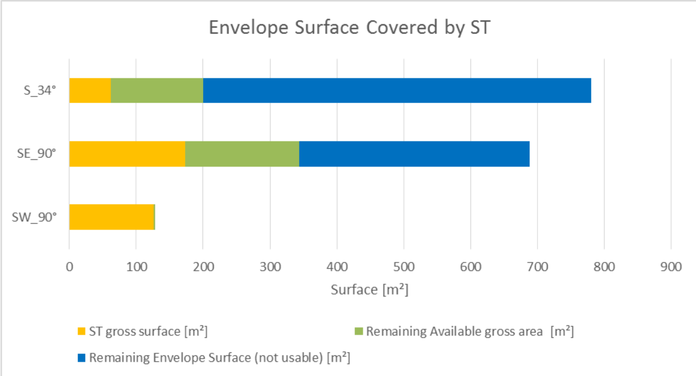


Figure 53 - Gross solar thermal area in each scenario to cover 50% of the DHW annual energy demand with enhanced flat plate collector (ST_2)

The same calculation has been done considering also different coverages rates of the domestic hot water demand. The surface area needed to cover 50%, 75% and 100% of the DHW energy is reported in Table 16. Overheating time is reported as well. As expected, the overheating risk increases with installed area and STC efficiency.

Table 16 - Needed areas per DHW coverage target and overheating hours in a year for the flat plate collector ST_2

Exposure and Tilt angle	50% DHW		75% DHW		100% DHW	
	INSTALLED AREA [m²]	OVERHEA-TING [h]	INSTALLED AREA [m²]	OVERHEA-TING [h]	INSTALLED AREA [m²]	OVERHEA-TING [h]
S_34	50	89	83	313	112	545
SE_90	150	26	219	410	292	691
SW_90	126	3	183	129	242	293

The scenario considering evacuated tubes technology leads to less installed area for the same coverage in comparison with the flat plate collector, but also higher risk of overheating as shown in Table 17.

Table 17 - Needed areas per DHW coverage target and overheating hours in a year for the evacuated tube collector ST_4

Exposure and Tilt angle	50% DHW		75% DHW		100% DHW	
	INSTALLED AREA [m²]	OVERHEA-TING [h]	INSTALLED AREA [m²]	OVERHEA-TING [h]	INSTALLED AREA [m²]	OVERHEA-TING [h]
S_34	40	78	60	356	78	619
SE_90	135	36	135	479	180	739
SW_90	80	4	165	183	152	368

Solar thermal potential is quite high in Bolzano for the presented case study, even if the building envelope is not optimally oriented and is shaded by a building at SW and by the mountain at the long SE side. Goals of 50% DHW energy demand coverage can be reached exploiting the whole SW with an enhanced flat plate collector; SE façades and roof have enough space also with a less performant collector. Overheating problems can be reduced already in a pre-design phase decreasing the installed area and exploiting the façade surfaces more than the roof: however, in the design phase, an optimized control is needed.

Conclusions

Even though obstructions can limit the chances to install solar technologies on façade, the solar potential for vertical surfaces might be high as demonstrated in the showed case study. The solar potential assessment is useful to avoid the exclusion a priori of envelope surfaces. Indeed, most of designers are used to decide the location of solar systems (both photovoltaic and solar thermal) relying on rough estimations. This kind of analysis can really help decision makers to evaluate the best solutions for installation of solar technologies. Still, available tools do not implement any correlation between solar thermal collectors' heat losses and microclimate. Only sophisticated software like *TRNSYS* and *EnergyPlus* include models to assess the real performance of STCs, but limited to standard applications and not integrated solutions. Due to complex envelope shapes and the use of some materials (aluminum and glass) and components in façade, studies involving the effect of the envelope on the surroundings and the microclimate should be required in calls for tenders. This investigation could avoid potential issues like higher air-conditioning costs in nearby buildings or hot spots on adjacent sidewalks due to reflected sunrays. Solar façades reach higher temperatures in comparison with standard finishing solutions, but it is difficult to say whether they can influence the microclimate or not. Fluid dynamic analyses can help to understand this phenomenon.

4.2 Modelling solar thermal façades

In the paragraph a literature review on modelling approaches to assess the potential for energy production linked to solar thermal façades is illustrated (best practices for sizing thermal energy systems; BIST modelling literature review; a simple method to assess the thermal energy production and overheating hours for different climates and orientations.

One of the obstacles for the spread of BIST Façades is the lack of knowledge to predict their performance. Energy simulation tools do not implement ready-to-be-used BIST models. To integrate STCs into façade within energy models is not an easy task: modelling the interaction among solar radiation, solar thermal collector, envelope and thermal zone is necessary.

Within the IEA Solar Heating and Cooling Program, a method to estimate the annual solar collector energy output was proposed. The methodology can be found at the website http://www.iea-shc.org/common-calculation-method. The annual production of a solar thermal system (not integrated in façade) can be calculated as a function of either the installed solar collector area or the installed collector nominal thermal power. Formulas are summarized in Table 18.

Table 18 – Calculation of the annual production of solar thermal energy

Solar Thermal Technology	Installed collector area	Installed nominal power
Unglazed collectors	0.29*Ho*Aa	0.42*Ho*Pnom
Glazed collectors in DHW systems	0.44*Ho*Aa	0.63*Ho*Pnom
Glazed collectors in combi-systems	0.33*Ho*Aa	0.47*Ho*Pnom

Being:

Ho: Annual global solar irradiation on horizontal the given location in kWh/m²

Aa: Collector aperture area in m²

Pnom: Nominal thermal power output of collector in kW

Experts in the field of solar thermal systems design and sizing give also values of typical installations for residential buildings as a function of the location. Usually a solar thermal system is sized by considering a DHW coverage bigger than 100% during the summer season. Then, during the colder months, the storage tank should be provided with a system integrating the missing warm water. The European Renewable Heating and Cooling Platform experts [36] gave some useful numbers for sizing solar thermal systems for residential buildings. Here follow some cases for residential buildings.

Solar thermal DHW systems for single and two family homes, thermosiphon

In Southern Europe, because of the high solar radiation and temperate climate, simple thermosiphon systems are commonly used. In this instance, the solar heat transfer fluid circulation is naturally driven, since the water store is installed above the solar collector. Usually 2-3 m² flat plate collector area and a 150-liter store are used for a family of four. The solar fraction for DHW achieved is about 50% to 60%. Cost associated to these systems is in the range of 3 and 11 €cents/kWh (including VAT) in Southern Europe.

Solar thermal DHW systems for single and multi-family homes, forced circulation

In Central and Northern Europe, including Northern Italy, only forced circulation solar thermal systems are used. The collector is installed on the roof and the hot water storage is usually situated in the basement. The solar heated transfer fluid circulates through the hydraulic solar circuit with the help of a pump. Typically, a 4-6 m² flat plate collector area and a 300 liters store are used for a family of four. Evacuated tube collectors are used in around 15% of solar thermal systems. The solar fraction for DHW achieved is about 60%. A special version of the forced circulation type is the so called "drain-back" system, where the heat transfer fluid is pumped through the collector only when the solar system is active; whereas it is stored in a tank while the system is inactive. Usually these systems cost between 5 and 10 €cents/kWh in Southern Europe, while the range increases to 8 and 19 €cents/kWh for small and collective solar DHW in Central and Northern Europe.

Combi-systems for one and two family homes

These are mainly used in central Europe, especially in Germany, Austria, Switzerland and France. In addition to the DHW, these systems provide space heating. In Germany about 50% of newly installed systems are combi-systems with usually a 10 to 15 m² flat plate collector and a 600 to 1000 liters hot water store. In a well-insulated building the solar fraction is about 25% of the overall building heat demand for DHW and space heating. In Austria, combi-systems have a collector area of 20 to 30 m². The cost of combi-systems is included around 13-14 €cents/kWh in Central and Northern Europe.

Large solar thermal systems for large DHW consumers

In multi-family homes (hotels, hospitals, residential homes, etc) with a high DHW demand, solar thermal energy can be provided through large solar thermal systems. These systems are usually forced circulation systems with the collector area on the roof and a central hot water store in the basement. A typical size is 0.5 to 1 m² collector area per occupant and 50 liters hot water volume per m2 collector area.

Solar Active Houses with high solar fraction

In a well insulated single family home in central Europe, about 60% of the overall heat demand for DHW and space heating can be covered by a collector area of 30 to 40 m² and a hot water store of 6 to 10 m³. This concept is called the *Solar Active House*. A small quantity of the solar yield produced in summer is stored to be used during the heating period, complementing the significant amount of heat produced by the large collector area in winter. The minimum solar fraction of a *Solar Active House* is 50%, but it can be increased to 100% by enlarging the collector area, the thermal storage volume, and the building insulation.

	Large size solar plants with daily storage	**Centralized solar plants with seasonal storage**
Minimum heating demand	> 30 apartments (> 60 people)	> 100 apartments
STC surface	0.8 - 1.2 m² per person	1.5 - 2.5 m²/(MWh*y)
Storage volume	50 - 60 l/m² of STC	1.5 - 2.5 m³/m² of STC
Energy saving	600 - 900 kWh/m²y	400 - 700 kWh/m²y
Energy saving for DHW	60 - 80 %	-
Energy saving for DHW+SH	20 - 40 %	50 - 80 %

Figure 54 – Preliminary design sizing of Solar Thermal Systems in North Italy (source: http://www.rinnovabili.biz/metri-quadri-solare-termico.htm)

Other estimation methods were formulated in the last years to calculate solar circuit pipes, circulating pumps and expansion vessels dimensions. The pipe dimeters can be established as function of the collector surface area and the length of pipes. Table 19 lists the most suited pipe diameter according to these two features. The roman character identifies the respective circulation pump: I is equal to a 30-60 W power consumption, while II and III corresponds to 45-90 W.

Table 19 – Solar thermal system_Pipe diameter in relation to STC surface area and length of pipes [70]

	Total length (m)				
Collector surface area (m²)	10	20	30	40	50
up to 5	15 (I)	15 (I)	15 (I)	15 (I)	15 (I)
6-12	18 (I)	18 (I)	18 (I)	18 (I)	18 (I)
13-16	18 (I)	22 (I)	22 (I)	22 (I)	22 (I)
17-20	22 (I)	22 (I)	22 (I)	22 (I)	22 (I)
21-25	22 (I)	22 (II)	22 (II)	22 (II)	22 (III)
26-30	22 (II)	22 (II)	22 (III)	22 (III)	22 (III)

When the collector is filled with antifreeze fluid and it is allowed to boil dry in overheating situations, there must be an expansion vessel of sufficient size to contain the displaced collector fluid. A specific volume to avoid stagnation can be preliminary designed, depending on the collector surface area and the height between vessel and collector, as showed in Table 20.

Table 20 - Solar thermal system_Expansion vessel volume in relation to STC surface area and system height [70]

		System height (m)					
System volume (l)	Collector surface area (m²)	2.5	5	7.5	10	12.5	15
18	5	12	12	12	12	18	18
20	7.5	12	12	12	18	25	35
23	10	12	12	18	25	35	35
24	12.5	12	18	25	35	35	35
25	15	18	25	35	35	35	50
29	17.5	25	35	35	35	50	50
35	20	25	35	35	50	50	50
37	25	35	35	50	50	50	80
40	30	35	50	50	50	80	80

Pressure loss is another key aspect to be considered if a good heat transfer is wished. Indeed, this should be kept as low as possible. The flow speed should not exceed the value 0.7-1 m/s, otherwise the resistance of the pipe would be too high. A volumetric flow of about 40 l/h for each m² of STC area is ideal.

Finding similar practices for commercial/office buildings is not easy since solar thermal plants have been used mainly in the residential stock. If the specific installation on façade is introduced, sources where to find reliable data are even less. Since there are not rules of thumb for façade systems integrating STCs, simulations are necessary. It is difficult to find in literature simulation approaches and the explanation of validated models to assess the energy performance of BIST envelope solutions. Lately, only a few works have been published in comparison with other technologies like BIPV façades, but the topic is catching the eye of researchers worldwide.

4.2.1 Literature review of BIST modelling

Lamnatou et al. [101], in their investigation about BIST modelling and simulation, revealed that majority of the modelling are about BIPV while there are very few studies on BIST systems. They also raised the question about the lack of monitored data to validate models. Two main groups of model were analyzed: Energetic modelling, referring to empirical models, which use for instance a collector efficiency curve, and Thermal modelling, which is about detailed physical models using thermal nodes and resistances. Many works are cited. Two of these might be noteworthy: one is about unglazed transpired collectors (solar air heating) used in China with an average efficiency higher than most of glazed flat-plate collectors, and the other one assessing performances of non-ventilated BIST collectors with a detailed physical model, from which emerged that evaporation exceeds the condensation in different wall constructions.

As highlighted by Maurer et al. [102], planners need an easy approach to include BIST into their calculations. Sometimes the absence of a model is matter of lack of budget, but another reason is the lack of knowledge and time for learning. Maurer developed in TRNSYS environment several new and simple models which are more accurate than neglecting the coupling to the building and which are less complex than detailed physical models. One of the discriminating factors among the approaches is how to consider the energy flux towards the building interior, which depends on the operation of the collector as well as on the irradiance. A first approach is recommended for BIST collectors with good insulation towards the building interior: the efficiency curve is modified to account for reduced back losses. A more complex method is recommended if the heat flux from the absorber to the building is important: a conventional collector model is used and the outputs are modified to account for the thermal coupling between the collector and the building. A third methodology suited when monitoring data of the solar thermal performance is available was developed: the extended efficiency curve increases the calculation accuracy for the solar thermal performance. Eventually, when measurements of both the energy flux to the building interior and the solar thermal performance are available (e.g. on a test facility), a more accurate strategy is proposed and suggested.

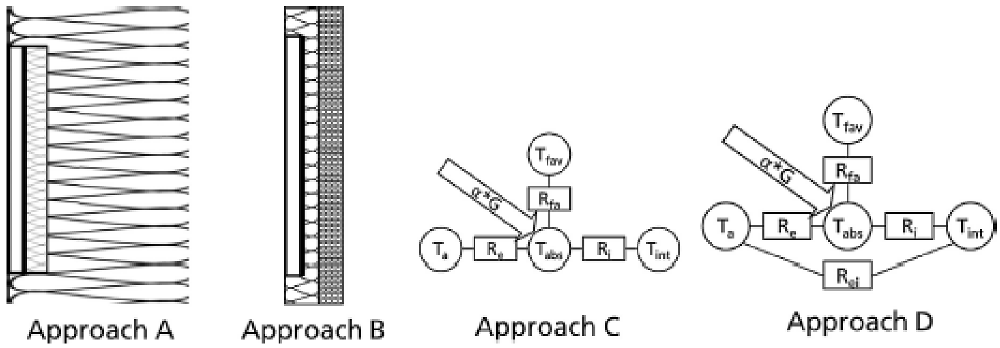


Figure 55 – BIST modelling approaches [102]

Metzger et al. [103] proposed a methodology to study the influence of solar collectors into façade on the envelope thermal behavior and, consequently, on the thermal zone. He considered two possible strategies: a direct integration (without air gap) and an indirect integration (with air gap). TRNSYS was used as energy simulation software. In the first case, there is a direct contact of solar collector with thermal insulation layers of building envelope (Figure 56, left). The model consists of a collector model coupled to a multi-zone building model by means of a fictive zone with high heat transfer surface coefficients and a minimal zone volume to achieve the conditions of direct contact (30mm thickness). For the fictive zone, the temperature of the exterior surface of the collector's insulation layer is linked to the actual temperature of the solar collector absorber. Regarding the indirect integration, two models were built: a simplified one and detailed one. The simplified method does not represent the thermal influence on the building indoor environment since air gap temperature follows the ambient temperature. In the detailed model air gap temperature is influenced by heat gains both from the collector (if absorber is at higher temperature than ambient) and from the building interior. Air flow was also modelled, by using TRNFLOW, and five vertical segments were considered (Figure 56, right). Heat gains during winter, cooling loads and layers' temperature are the metrics compared.

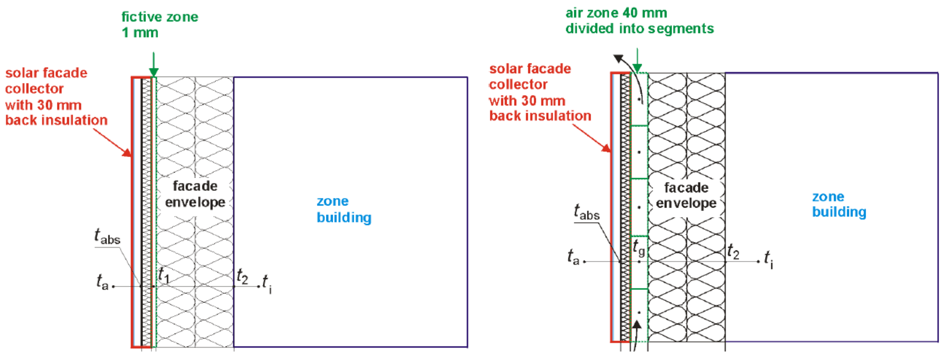


Figure 56 - Direct integration (to the left) and indirect (to the right) of solar collector into façade [103]

Matuska et al. [65] investigated the integration of a solar thermal collector into façade as possible solution to refurbish the envelope of existing residential buildings. First, they built a detailed mathematical model with the tool KOLEKTOR for the investigation of solar collector thermal performance (efficiency curves). This model comprises absorber outer energy balance (heat transfer through glazing, air gap, and frame and absorber surface) and absorber inner energy balance (heat transfer within the absorber fins with solar radiation and piping). After this analysis, the façade construction was modelled in TRNSYS. The surface temperature of the last insulation layer is coupled with the solar collector's absorber temperature. Two types of façade were investigated for the application of a façade collector: one is a mid-weight façade formed by 27 cm thick ceramic-concrete panels, while the other solution is a heavyweight façade formed by a 45 cm thick brick wall. Parametric analysis for different façade construction resistances R, collector field surfaces Ac, required solar fractions and orientations were performed.

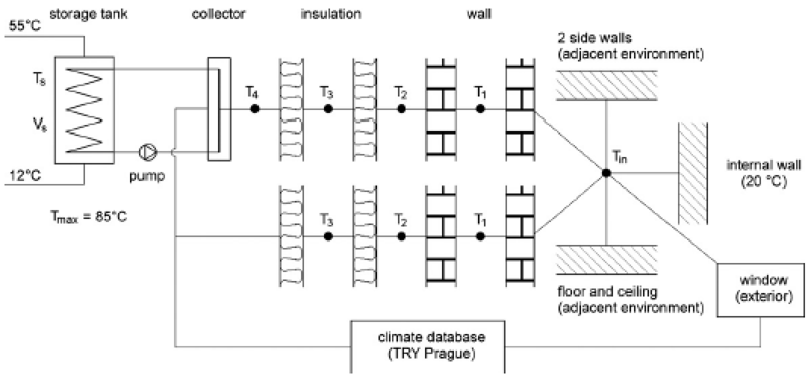


Figure 57 - Schematic model of a solar collector thermally coupled to a façade [65]

Pflug et al [104] investigated on Transparent Solar Thermal Collectors using a liquid heat transfer medium. A simplified model, based on an existing validated and detailed one, was developed to predict the collector efficiency. TRNSYS was used as simulation environment. Heat flow from the component towards the interior and heat flow removed by the fluid are the main outputs of the detailed model, which is complex, since more than 300 parameters have to be fit on the basis of measurements. Contrary to opaque collectors, the efficiency of a façade collector also depends on the temperature of the building interior. To take into account this aspect, a simplified formula to calculate the heat flux was hypothesized. A parameterization (by varying external temperature, internal temperature, irradiance, fluid temperature) was done by using a solver to minimize the Root Mean Squared Error (RMSE) between detailed and simplified model. This led to specific values of heat loss coefficients in order to predict collector efficiency and heat flow removed by the fluid. The model is not able to predict the heat flow from the component towards the interior.

4.2.2 Façade thermal analysis – 1D study

The thermal performance of the opaque portion of the façade case study evaluated in this thesis, was investigated through detailed thermal analyses. A 1-D study to assess the influence of the façade system on both the heating demand (gain) and the cooling demand (load) was carried out. The results are function of the façade insulation thickness, without considering the activation of the radiant system, but only the heat flow due to the thermal load inside the water tank storage. This thermal analysis was performed with COMSOL Multiphysics software [105], which is suited to execute also 2-D and 3-D studies on several physics.

The technological solution is characterized by an air gap located between the solar thermal collector and the water tank storage, as illustrated in Figure 58.

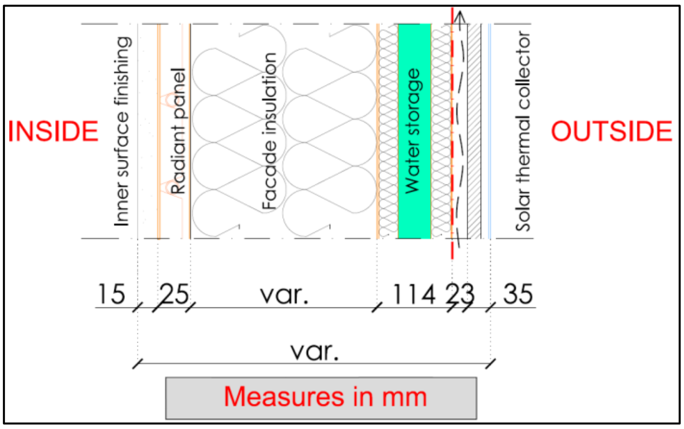


Figure 58 – Wall construction

Nodes delimitating the different layers and lines corresponding to the domains compose the model (Figure 59). Boundary conditions and heat loads were assigned. Input data were taken from a single-zone energy model launched with TRNSYS to simulate an office room located in Bolzano, with four south-oriented passive unitized façades. Façades have a 50% window to wall ratio.

For the first solution, inputs coming from the TRNSYS model were:

- *Space heating demand, used as heat sink input in the COMSOL model together with the DHW demand;*
- *Solar radiation on façade, to calculate the heat source to be assigned to the water storage considering an efficiency of 40%;*
- *The room temperature used as internal boundary condition (8 W/m²K as convective heat transfer coefficient - hc);*
- *The ambient temperature used as external boundary condition (hc=25 W/m²K). Indeed, it was assumed that the air gap follows the variation of the ambient temperature.*

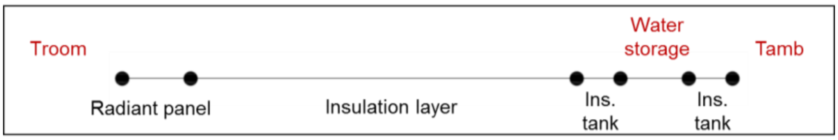


Figure 59 – Model nodes and domains_Solution 1

Five scenarios were compared:

- *Passive solution with 15 cm mineral wool insulation (reference case)*
- *Active solution with 5 cm insulation*
- *Active solution with 10 cm insulation*
- *Active solution with 15 cm insulation*
- *Active solution with 20 cm insulation*
- *Active solution with 20 cm insulation*

Results show that inwards heat fluxes contribute to reduce the heating demand in the range of 9% to 4% by increasing the insulation thickness (Figure 60), while cooling load decreases from 32% to 16% if insulation resistance is increased.

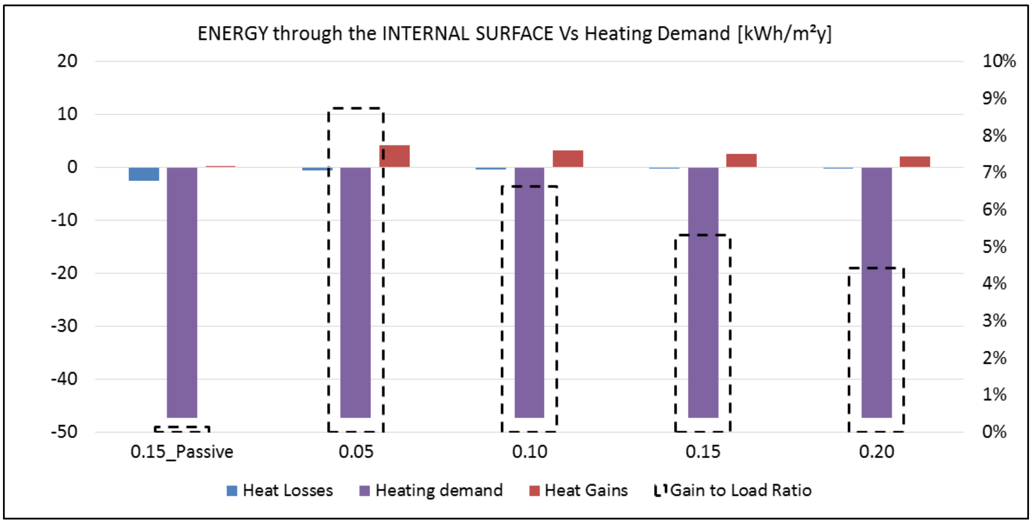


Figure 60 – Heating contribution due to inwards heat flux

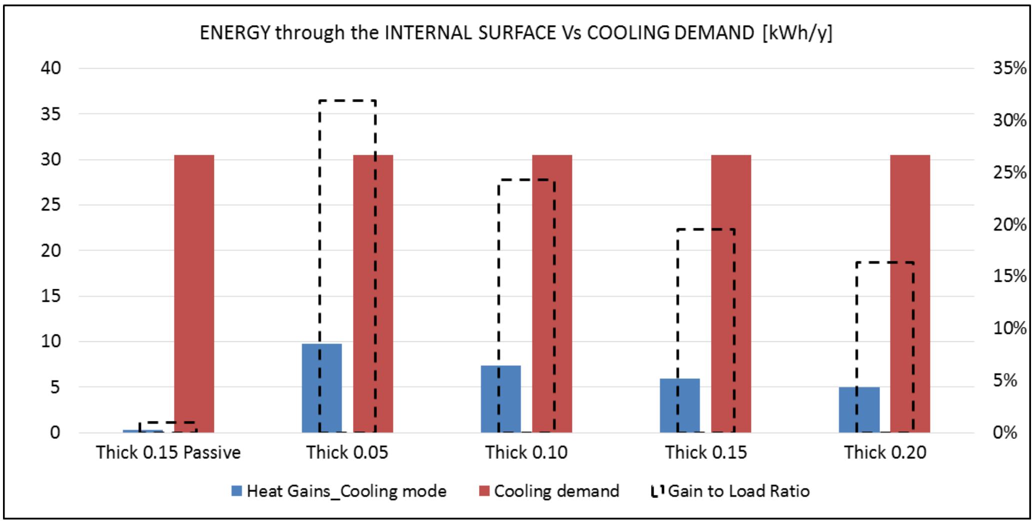


Figure 61 – Cooling load due to inwards heat flux

A solar fraction of 90% for DHW and 50% for space heating were hypothesized. Other factors like efficiencies of energy systems and unitary energy cost to calculate the economic saving were assumed. The sum of cost savings (for DHW and space heating) and extra-costs (for cooling) is always around 4 €/m²y, regardless the insulation thickness as reported Table 21.

Table 21 – Cost savings and extra-costs

Insulation Thickness	Space Heating	DHW	Space Cooling	Total
0.05	-3.03	-1.41	0.56	-3.88
0.10	-2.98	-1.41	0.42	-3.96
0.15	-2.94	-1.41	0.34	-4.00
0.20	-2.91	-1.41	0.28	-4.04

Concerning the thermal comfort, the inside surface temperature was assessed as performance indicator. During heating mode, it was noticed that a 10 cm insulation thickness should guarantee values between 20 and 24°C for almost 60% of the season, as marked with the light blue lines in Figure 62, regardless the effective occupation of the office room. An insulation layer thicker than 0.10 m does not influence that much the surface temperature. Values lower than 18°C are very rare.

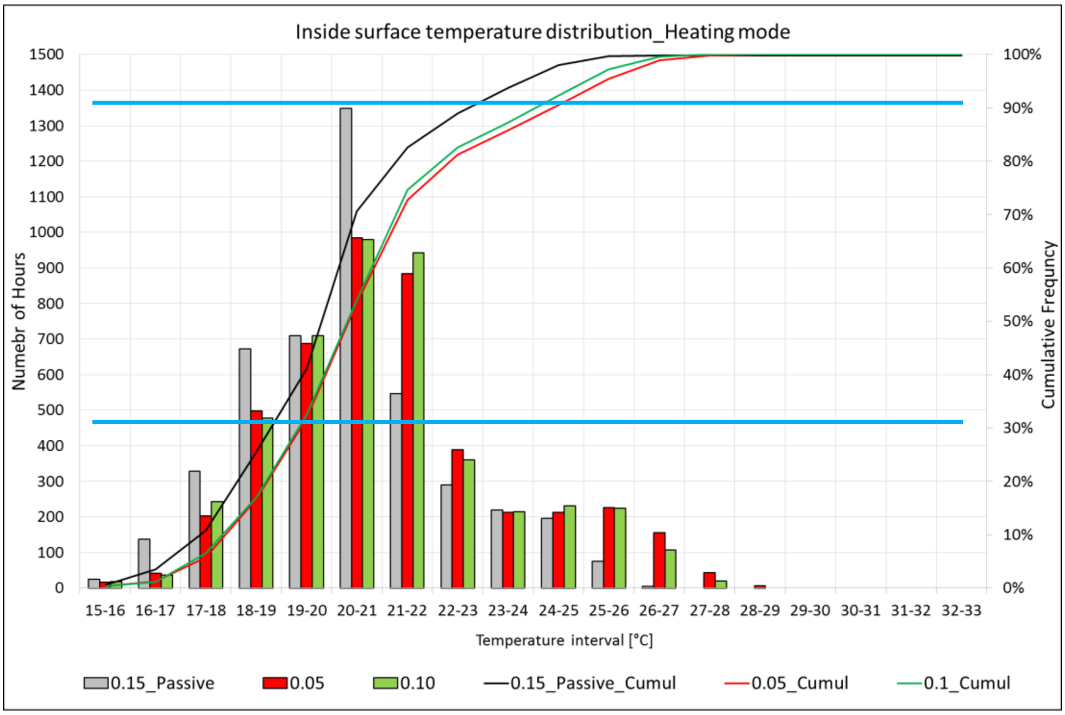


Figure 62 – Inside surface temperatures during Heating Season

With regard to the cooling mode, the surface temperature achieves values higher than 27°C in some periods. The basic case (passive façade) is characterized by temperatures higher than 27-28°C only for 5% of the season, while. Under the assumptions that the radiant system is not operative, the active façade with a minimum insulation level (0.05 m) can leads to a probability to have those values for almost 40% of the season (see dashed blue line). Even by installing thicker insulation layers (0.15 – 0.20 m), surface temperatures achieve high values in comparison with the standard passive solution, but the risk to reach values higher than 27-28°C over the season decrease to nearly 25%.

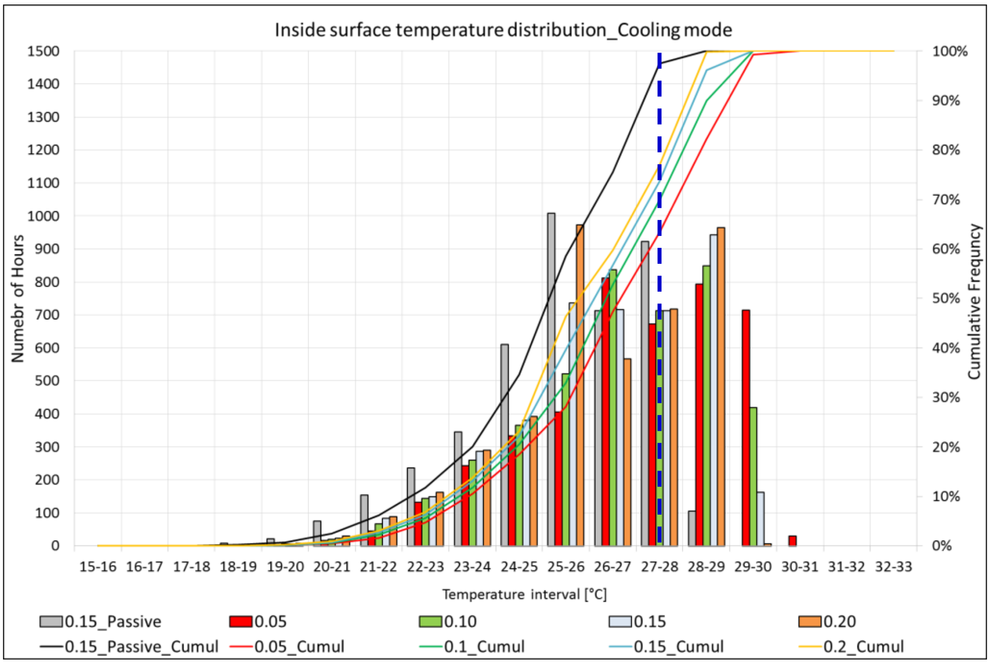


Figure 63 - Inside surface temperatures during Cooling Season

Literature about solar thermal façade modelling does not point out the vapor transfer as matter of concern. Authors focus on the thermal fluxes and the heat transfer that can affect the indoor environment in terms of both temperature and comfort. Indeed, façade systems integrating solar thermal technologies can achieve very high temperature (higher than 195°C) if a ventilated gap is not foreseen. Many approaches to simulate the behavior of a solar thermal façade can be found and used, but still simplified methods to estimate energy performances are lacking and this might be the biggest obstacle to spread of Building Integrated Solar Technologies Façades.

Modelling a solar thermal façade such as the case study in a software environment implicate the coupling of several physics. In this case, the STC, the storage system and the radiant panel performances are influenced one to each other. The 1-D COMSOL study has been useful to derive monthly load decreasing/increasing coefficients to be applied to heating/cooling demands obtained with the TRNSYS model explained in paragraph 4.3.

A more detailed analysis is necessary to take into account thermal bridges in solar thermal façades and possible deviations of the heat flux. A two-dimensional model was built to assess the influence of the convection phenomena through fluid-dynamic. This is a mandatory step to get reliable results to evaluate the feasibility of similar façade systems. A 3D model could be even better, but it requires more time and effort to obtain results, and it should be judged whether it is worth or not.

4.2.3 Façade thermal analysis – 2D study

As for the 1-D analysis, the software COMSOL was used to carry out the 2-D analysis. Setting a physic like the heat transfer and how this is affected by the fluid-dynamic occurring within an air cavity is not immediate. Sometimes similar problems need workarounds. Almost all construction layers (radiant panel, insulation, water storage, insulation, air gap, solar thermal collector's insulation, absorber plate, glazing cover) were inserted in the geometry model. The aluminium sheet defining the shell's internal side was neglected. Since the objective of the analysis was the assessment of the air channel on the rear side of the solar thermal collector, the inside air cavity between radiant panel and alumimun shell was ignored as well. It was assumed that the air gap between storage and STC has two horizontal cracks, one is below the collector and one is above it. Actually, the façade case study was conceived with an air gap not communicating with the outdoor air.

Only the opaque portion of the façade was implemented, considering a height of 1 meter. The model is formed by a series of rectangles identifying the different layers. The layers are built with parametric y-coordinates in order to change easily the air gap thickness for different evaluations. A material was assigned to each rectangle as listed in Table 22.

Table 22 – Material and thicknesses assigned to each wall layer as showed in Figure 64

Item	Material	Thickness [m]
Radiant panel	Aluminum	0.02
Insulation	Mineral wool	0.1
Water Storage	Water	0.06
Insulation	Mineral wool	0.03
Air Cavity	Air	0.02 (variable)
STC's Insulation	Mineral wool	0.06
Absorber plate	Steel	0.005
Air gap between absorber and glass	Air	0.005
STC cover	Glass	0.005

Once the geometry is created, the software demands boundary conditions and the physics to be inquired.

COMSOL provides a *Turbulent Flow* interface to simulate single-phase flows at high Reynolds numbers. This interface can be used for both stationary and time-dependent analyses. Fluid properties, such as density and viscosity, can be defined through user inputs, variables, or by selecting a material. To assign in the right way the boundary conditions on the external façade side, a fictitious region next to the outer side of the façade was implemented (Figure 64). A vertical external boundary in this region is required, but since this is located quite far away from the façade, it has only a small effect on the flow in the region. *Open boundary* conditions were applied at both the horizontal region boundaries to allow both an inflow and an outflow at the boundaries.

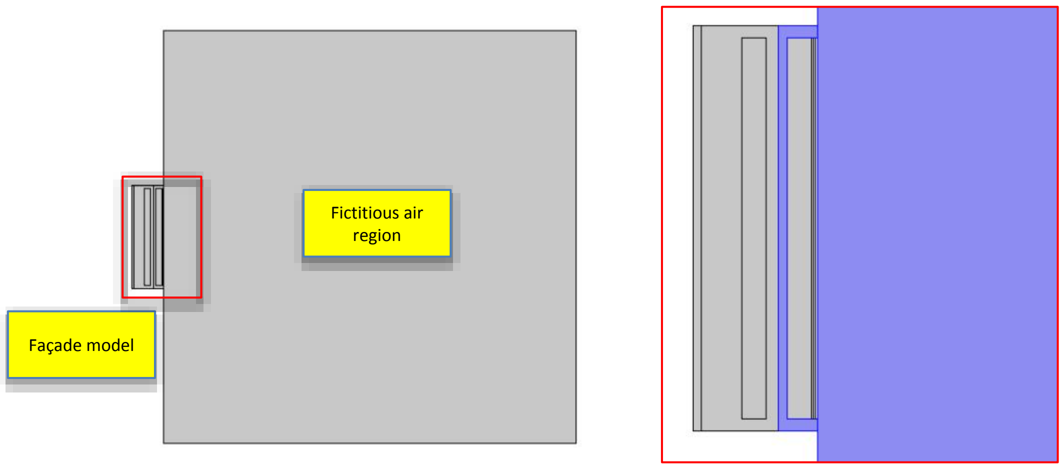


Figure 64 - 2D model geometry in COMSOL_Whole model (left) and façade detail (right)

The software implements a *Heat Transfer* interface, used to model heat transfer in fluids by conduction, convection, and radiation. By default, COMSOL activate a fluid model on all the domains. Physics can be associated separately to fluids and solids; *heat transfer in fluids* concerns the fictitious volume next to the façade and the air gap, while all the other layers are put under the *heat transfer in solids* section. The user has to define where the domains are adiabatic. Heat sources and heat sinks can be assigned to the domains, for example to model the water storage charge/discharge effect in a time-dependent simulation. Temperature boundary conditions are assigned for the internal air node, the absorber plate and the ambient air temperature (at the right vertical edge of the air region). To synchronize the features from the *Heat Transfer* and *Fluid Flow*, the Non-Isothermal Flow Multiphysics was implemented.

Finally, the meshing sequence is automatically added, but alternative mesh solutions can be defined by the user.

Several studies were computed to assess the façade technology thermal behaviour. Table 23 summarizes the four stationary studies by specifying the boundary conditions of each scenario. Simulations 1 and 2 simulate a summer day and a winter day with a discharged storage, as it might happen when sun radiation is not available. Simulation 3 and 4 implement a heat source (100 W) into the water storage simulating the effect of charge.

A time-dependent study was set up but unfortunately it was not possible running the simulation due to issues the author was not able to solve.

Through these analyses, some outcomes are expected: risk of surface condensation; risk of stagnation; benefits/constraints of the heat flux going inwards (similarly to what was assessed with the 1-D analysis); benefit from a ventilated air cavity.

Table 23 – COMSOL analyses' boundary conditions

Simulation	BOUNDARY CONDITIONS					
ID	TAI [°C]	TSI [°C]	WSHS [W]	Air Gap [m]	TABS [°C]	TAO [°C]
1	26	-	-	0.02	90	35
2	21	-	-	0.02	90	0
3	26	-	100	0.02	90	35
4	21	-	100	0.02	90	0

Where:

- *TAI is the Indoor Air Temperature*
- *TSI is the Inside Surface Temp. (Radiant panel)*
- *WSHS is the Water Storage Heat Source (net value considering also potential heat sink)*
- *Air Gap is the Air Gap Thickness*
- *TABS is the Absorber Temperature*
- *TAO is the Outdoor Air Temperature*

Output to be investigated are:

- *Condensation risk through a surface temperature analysis*
- *Water storage loading time when there is heating demand(Storage temperature lower than Water supply temperature)*

- *Thermal discomfort associated to inside surface temperature (assuming the radiant panel is not active)*
- *Inwards Heat Transfer_Cooling demand increase/Heat demand reduction*

To obtain single values of temperature and heat flux, average and linear integration over the lines defining the façade surfaces are necessary. Figure 65 clarifies the surfaces for which a linear integration is requested. More in detail, the inner surface (Surface1) requires 2 integrations, one for the temperatures and one for the fluxes; the same occurs on the outer side (Surface5). Other inquired surfaces are: water storage's vertical edges (Surface2 and Surface3) to extrapolate temperatures and fluxes and the interface (Surface4) between façade and air gap to get a temperature value.

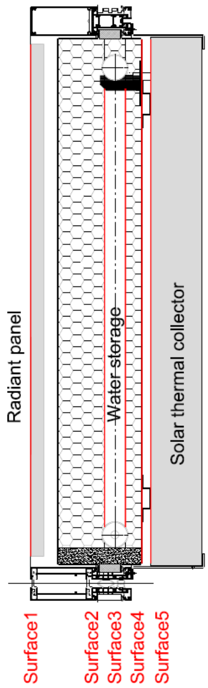


Figure 65 – Identification of surfaces subject to average or linear integration

As for the 1D analysis, the 2D studies do not assess the heat transfer efficiency through the liquid-carrier from solar thermal collector to water storage, but they evaluate the heat flux through the façade due to the heating of the STC absorber plate and the water storage charging.

Simulation 1

Summer sunny day with discharged storage - stationary mode

Boundary conditions and heat sources:_TAI=26 °C; Tabs=90 °C; TAO=35 °C; WSHS=0 W

The computation required 46 minutes.

With the set boundary conditions, the maximum air gap temperature is around 43 °C, while the maximum water storage temperature is 36.04 °C. It has to be stressed that the simulation does not consider any thermal inertia effect due to previous steps, since only an instant is simulated.

Figure 66 shows the temperature trend along the façade construction at two cut lines: 0.20 m and 0.80 m height. In 0.60 m, the temperature of the air in the cavity increases by almost 4 °C. This temperature difference leads to an increase of pressure inside the cavity, in particular from -0.1 Pa at the bottom to 0.05 Pa at the top.

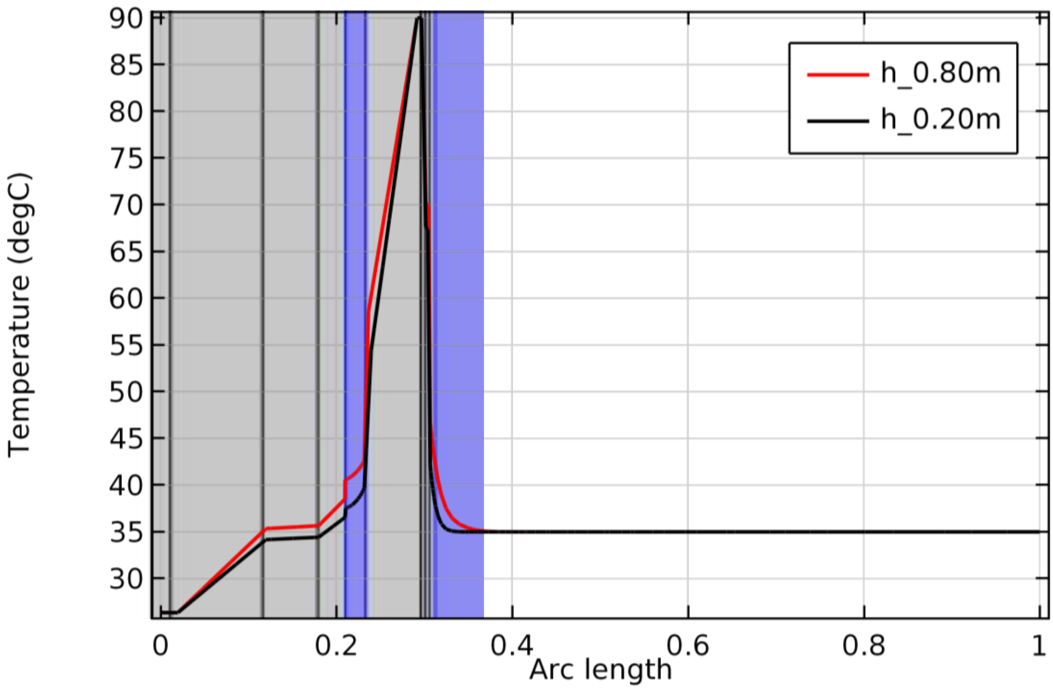


Figure 66 – Summer case/Discharged Storage_Façade temperature trend at different heights

Figure 67 displays the air velocity in the air cavity, both at the bottom and at the top, and in the surroundings of the façade. The arrows show the velocity field. The air flow is pretty constant along the cavity. Values between 0.13 and 0.15 m/s were detected.

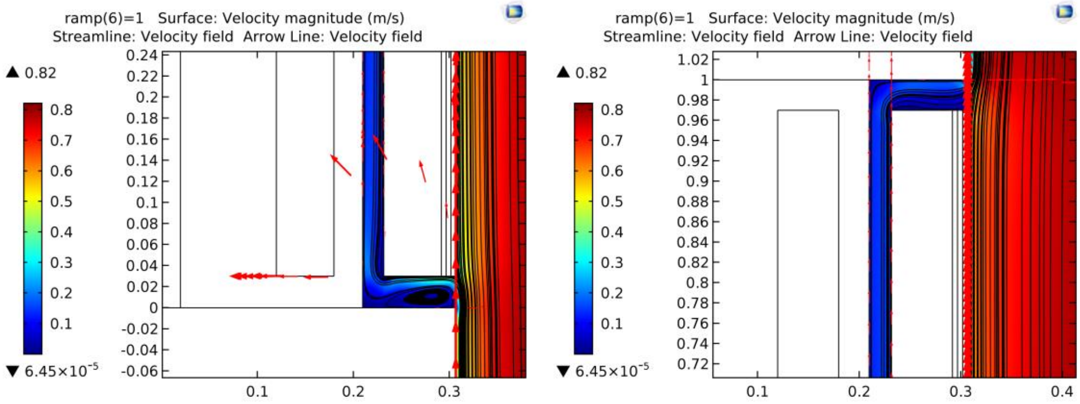


Figure 67 – Air velocity (m/s) on the STC rear side cavity

On the inner cavity surface, a minimum surface temperature value of 36.6 °C was obtained. An air flow characterized by 43 °C and a relative humidity of 70% would create condensation on the surface.

Table 24 reports the average temperatures occurring on the surfaces highlighted in Figure 65, and the temperature of the water inside the storage (TWS). The same table points out the heat flux values obtained through linear integration along the surfaces. According to the assumptions done, a small heat flux would go into the office room. Different values can be achieved depending on the heat stored into the water tank and the air cavity features.

Table 24 – Summer case/Discharged storage_Average temperature (TS) and heat flux (HF) on the surfaces

OUTPUT from COMSOL

TS1 [°C]	TS2 [°C]	TWS [°C]	TS3 [°C]	TS4 [°C]	TS5 [°C]	HF1 [W]	HF2 [W]	HF3 [W]	HF4 [W]	HF5 [W]
26.36	34.74	34.89	35.04	38.34	46.66	2.92	2.82	-2.81	2.94	-20.02

Simulation 2

Winter sunny day with discharged storage - stationary mode

Boundary conditions and heat sources:_TAI=21 °C; Tabs=90 °C; TAO=0 °C; WSHS=0 W

The analysis required 48 minutes.

In this case, the maximum air gap temperature is around 10 °C, while the maximum water storage temperature is 12 °C. Condensation on the external surface of the aluminium shell is likely to occur. Indeed, a minimum surface temperature value of 2.95 °C was observed. Air flow temperature around 9 °C and 70% relative humidity would lead to condensation. Condensation on the STC glass cover should occur only with cold and humid external air conditions, but anyway this would not be a relevant issue, except for the aesthetical aspect.

The temperature trend along the façade thickness is showed in Figure 68. Air gap temperature increases of 5 °C, passing from 5 °C at 0.20 m height to 10 °C at 0.80 m height.

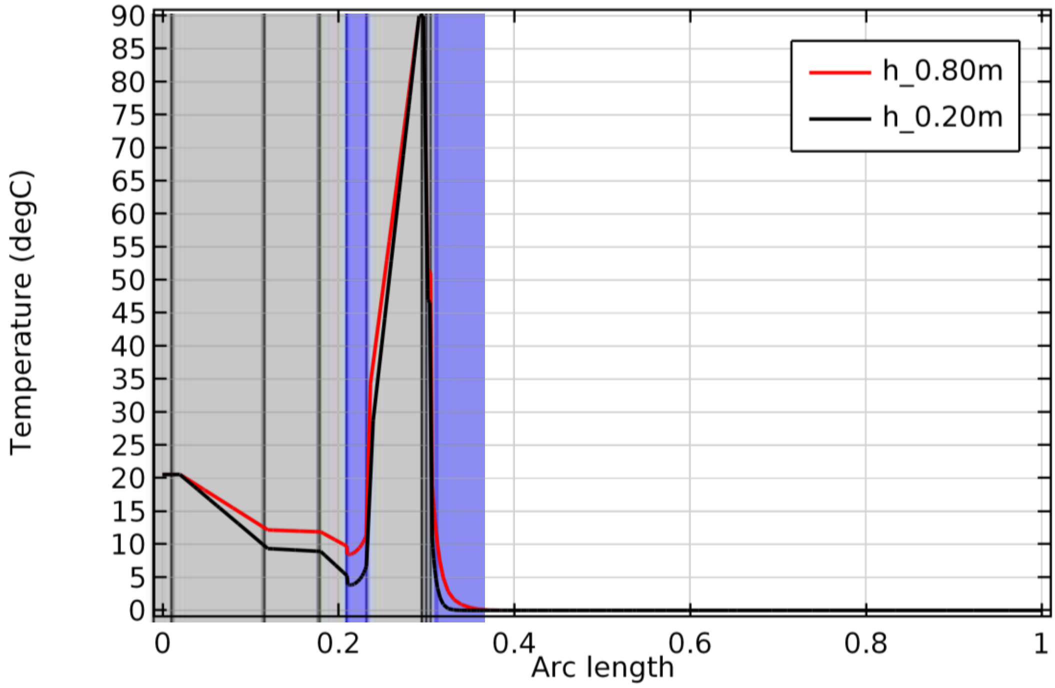


Figure 68 – Winter case/Discharged Storage_Façade temperature trend at different heights

Higher pressure difference was noticed in comparison with the summer scenario. Indeed, the pressure at the bottom is around -0.15 Pa, while the value at the top is 0.1 Pa. This increment brings to a higher air velocity respect to the first case: values between 0.18 and 0.20 m/s were achieved.

Average surface temperature values are revealed in Table 25 together with heat fluxes obtained by means of linear integration. A negative heat flux is showed. Hence, under the implemented assumptions, the heat flux is expected to go from inside to outside. This is plausible if the storage is not heated.

Table 25 - Winter case/Discharged storage_Average temperature (TS) and heat flux (HF) on the surfaces

OUTPUT from COMSOL

TS1 [°C]	TS2 [°C]	TWS [°C]	TS3 [°C]	TS4 [°C]	TS5 [°C]	HF1 [W]	HF2 [W]	HF3 [W]	HF4 [W]	HF5 [W]
20.57	10.8	10.61	10.43	6.82	16.71	-3.41	-3.29	3.28	-3.32	-35.83

Next two simulation scenarios implement heated water inside the façade, by setting a fixed heat source to the storage layer. This way, the hydraulic connection between solar thermal collector and storage can be assumed.

Simulation 3

Summer sunny day with charged storage - stationary mode

Boundary conditions and heat sources:_TAI=26 °C; Tabs=90 °C; TAO=35 °C; WSHS=100 W

Differently from the first stationary simulation, in this case it was assumed that the heat absorbed by the absorber has been transferred to the storage system through the circulating liquid (water+glycol). Considering the solar radiation on a south-oriented vertical surface in Bolzano, it was observed that the solar radiation absorbed by 1 m² of absorber plate can range between 50 and 250 W (absorption coefficient: 0.4). Since it is foreseen to deliver the produced heat to a centralized storage or to use it for space heating, it is reasonable thinking to not have the maximum absorbed heat into the storage. A value of 100 W was hypothesized.

The computation took 65 minutes.

The presence of a heat source into façade changes significantly the heat fluxes and it affects the air flow into the STC rear-side cavity. Indeed, air velocity is twofold in comparison with the case without heat source and it achieved 0.30 m/s. The cavity's edges reach quite high surface temperatures (between 48 and 60 °C), while the air cavity temperature ranges between 40 and 50 °C as showed in Figure 69. Due to these values, condensation risk is out of question.

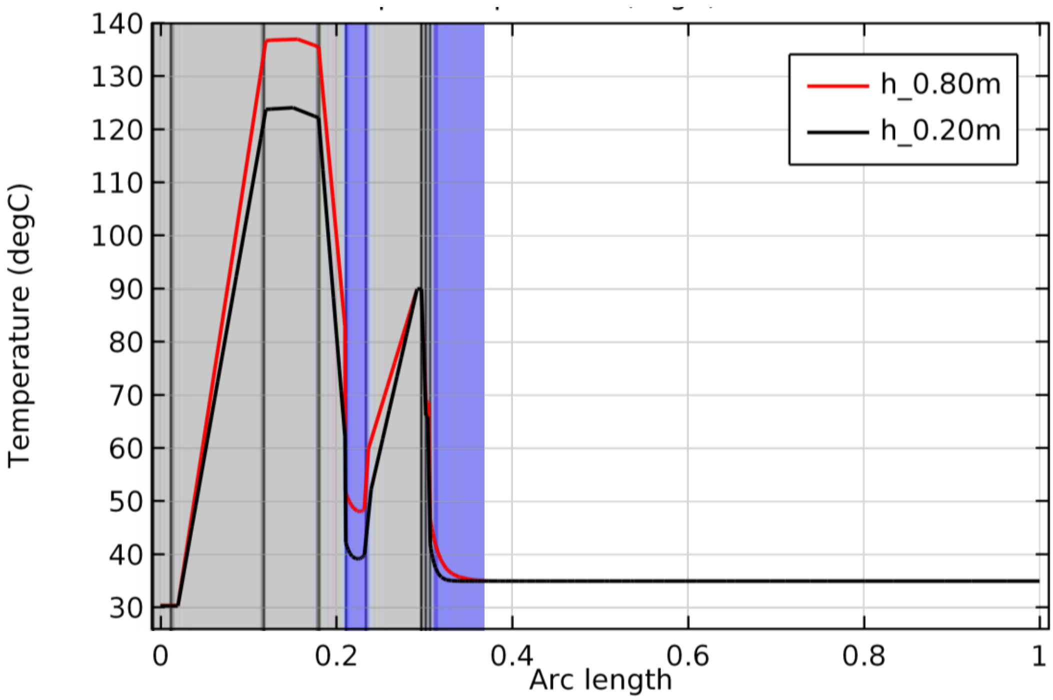


Figure 69 - Summer case/Charged Storage_Façade temperature trend at different heights

Concerning the temperatures inside the storage, water reached values in the range of 120 and 138 °C. These temperatures therefore lead to a high inside surface temperature, achieving 30 °C, while the room temperature is set to 26 °C. Table 26 summarizes the surface temperatures along the façade thickness. Heat fluxes are showed as well.

The inwards heat flux implicate a higher energy demand for cooling space. Indeed, the radiant panel surface temperature should be lower to guarantee a comfortable environment. The model quantified the heat flux towards the room to ca. 35 W/m². This is an output for the radiant panel manufacturer, who should consider it to design the system considering the necessary water supply temperature to keep a specific refrigerating power allowing to get 26 °C inside the room.

Table 26 - Summer case/Charged storage_Average temperature (TS) and heat flux (HF) on the surfaces

OUTPUT from COMSOL										
TS1 [°C]	TS2 [°C]	TWS [°C]	TS3 [°C]	TS4 [°C]	TS5 [°C]	HF1 [W]	HF2 [W]	HF3 [W]	HF4 [W]	HF5 [W]
30.37	131.07	130.96	129.7	59.97	48.08	34.92	33.65	62.69	-65.01	-21.57

Simulation 4

Winter sunny day with charged storage - stationary mode

Boundary conditions and heat sources:_TAI=21 °C; Tabs=90 °C; TAO=0 °C; WSHS=100 W

Once again, the winter case was analysed but implementing the heat source into the water storage. As for the summer scenario, 100 W were considered.

The computation took 65 minutes.

Contrary to the summer case, the inwards heat flux this time has a beneficial effect by increasing the inner surface temperature to 24 °C as showed in Figure 70. Looking at the chart, one can notice the temperature variations at the two height levels inside both the storage and the air cavity. In the first layer a 15 °C difference occurs, while the air cavity temperature pass from 6 to 17 °C, reducing STC heat losses. Values around 10 °C were displayed with the discharged storage case. Air velocity along the cavity is constant to 0.25 m/s.

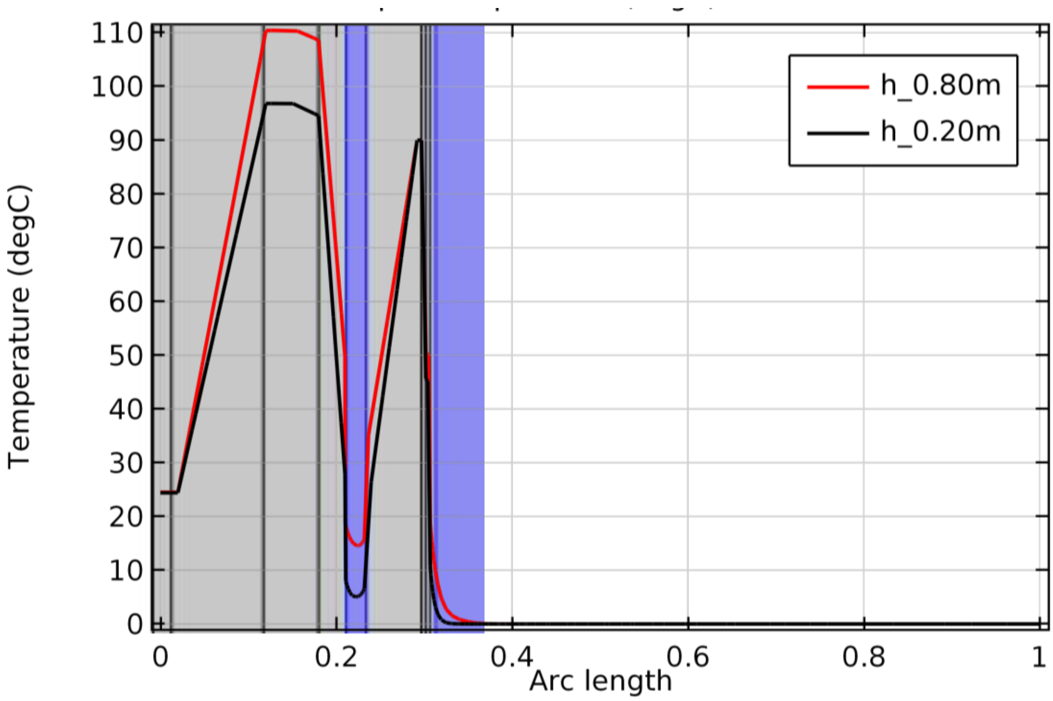


Figure 70 - Winter case/Charged Storage_Façade temperature trend at different heights

Minimum air temperature values inside the cavity are around 2.8 °C but the close surfaces have temperatures higher than 8 °C, hence no condensation is expected under these conditions. Table 27 lists the average surface temperatures achieved under the assumptions made. The heat flux going inwards is 27.7 W/m². This effect would reduce the heating power necessary to supply warm water to the radiant system. It could be even kept deactivated for the intervals when this situation takes place.

Table 27 - Winter case/Charged storage_Average temperature (TS) and heat flux (HF) on the surfaces

OUTPUT from COMSOL

TS1 [°C]	TS2 [°C]	TWS [°C]	TS3 [°C]	TS4 [°C]	TS5 [°C]	HF1 [W]	HF2 [W]	HF3 [W]	HF4 [W]	HF5 [W]
24.46	104.46	104.01	102.4	26.32	17.37	27.7	26.67	69.67	-72.11	-38.519

An annual thermal analysis simulation would help to understand better the behavior of the façade. Indeed, a time-dependent simulation with dynamic charge/discharge of the storage could provide the inwards and outwards heat flux trend over the year with more precise results than those obtained with the 1-D study. Indoor set point temperatures would change hourly depending on occupation time and heating or cooling season, while the ST's absorber temperature would vary according to solar irradiance on the surface and system activation control. The heat source assigned to the water storage would be adjusted depending on solar irradiance and heating/DHW demand. In case of time-dependent models, temperatures and heat sources are assigned by means of an external text file recalled by COMSOL. Temperature of the solar thermal collector's absorber are obtained with a simple TRNSYS model has been created. TRNSYS works with components called TYPES, permitting the user to set up every component included in an energy system. The model used consists of a solar loop including:

- *A solar thermal collector (Type 1b)*
- *A water storage (Type 534)*
- *A circulation pump (Type 3b)*
- *A controller to trigger the loop (Type 2b)*

The control has the purpose to keep active the circulation pump under specific assumptions. For this model, the pump keeps on working if the difference between the temperature of the water coming from the solar thermal collector and the temperature of the water inside the storage is bigger than 10 °C. The loop is active until the difference does not go under 2 °C. To be reactivated, the water inside the STC has to be again bigger than 10 °C the water storage temperature. Figure 71 shows the four types with all the connections as viewed in the TRNSYS graphic interface.

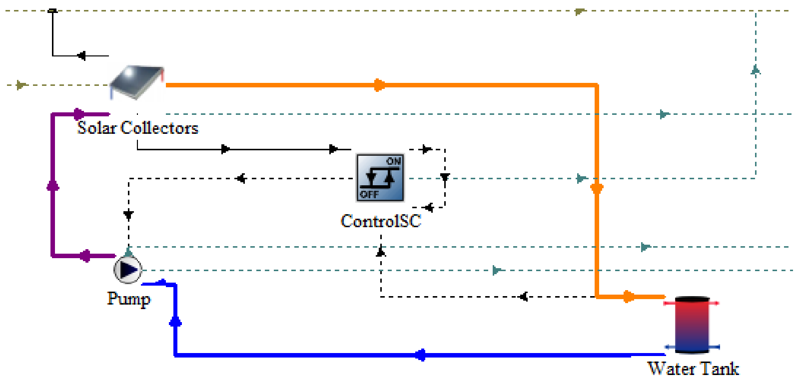


Figure 71 – Solar loop implemented in TRNSYS

The absorber temperature over the year is obtained as average between the STC's inlet and outlet temperature. A simulation is required for each façade orientation. From the same TRNSYS model, the annual production of solar energy from the façade is extracted.

The activation of the radiant system is not implemented and the analysis of results is not reported since the main purpose of this simulation is the extrapolation of an average façade temperature to be assigned as boundary condition to the TRNSYS energy model in the different façade configurations where the façade concept is present. This way, the energy flux towards inside is created all over the year of simulation. The TRNSYS energy model is clarified in the next paragraph.

Unfortunately, the developed COMSOL model showed some errors and it would require too much computation time to get results.

4.3 Building energy model and simulation results

The main purpose of the office room energy model is the quantification of the energy performance associated to different façade configurations in order to populate the database of results included in FAST-IN tool. Once the user sets the building façade by choosing among different office rooms, results will be automatically recalled and the energy performance of the entire building will be displayed. A complete explanation of the tool in terms of contents and use is reported in the paragraph 5.1. The author wants to stress the importance to give to the tool user enough freedom to define the façade configuration. For this reason, many combinations of façade components in terms of glazing system type, WWR, solar thermal collector size, number of collector covering the façade of an office room and other features can be selected among more options.

The thermal analyses have helped to model the façade hydraulic system effect on the energy performance of the building. Indeed, the façade concept was implemented in the TRNSYS model by setting the average façade temperature obtained with COMSOL as boundary condition. This choice derived after several attempts to model each one of the active components integrated into façade (radiant panel, storage system, solar thermal collector) but modelling the nodes associated to these items was not immediate and it was not found a way to couple all the involved physics. The simplified coupling of the two software brought to results that require a validation according to data monitored from tests.

An aspect that was neglected in 2D thermal analyses is the passage of warm water into pipes embedded in the insulation layer running through the façade. Sophisticated control strategies to activate the different components of the hydraulic layout were not considered in the energy model.

A single-zone energy model was implemented in TRNSYS energy modelling environment. The model reflects a reference office room with dimensions and internal loads deriving from other simulation experiences. The main features of the model are listed in Table 28.

Table 28 – Office room features implemented in the energy model

Office and Envelope Features	Value	U.M.
Office Width	4.5	m
Office Height	3	m
Office Depth	6	m
Lighting Power Density	15	W/m^2
Equipment Power Density	10	W/m^2
Envelope air tightness (n50 value)	2	ACH
Shading system: Venetian blind with aluminum lamellae		
Shading system activation: if solar radiation on façade > 200 W/m^2		
Insulation material	Mineral Wool	
Insulation thickness	10	cm
Curtain Wall Façade Width	1.5	m
Curtain Wall Façade Heigth	3	m

The tool allows the user to fix the number of office rooms for four façade orientations (north, west, south, east) and to choose for each sun exposed surface the number of active solar thermal façade modules. For this reason the north exposed surfaces have only one possible configuration, with façade modules integrating only the radiant panel system (distributive façade module), while the sun exposed offices can be defined with different façade compositions:

- *Three solar thermal façade modules*
- *Two solar thermal façade modules + one distributive façade module*
- *One solar thermal façade module + two distributive façade modules*
- *Three distributive façade modules*

A different pattern for each façade orientation can be designed by joining different office rooms as the ones showed in Figure 72.

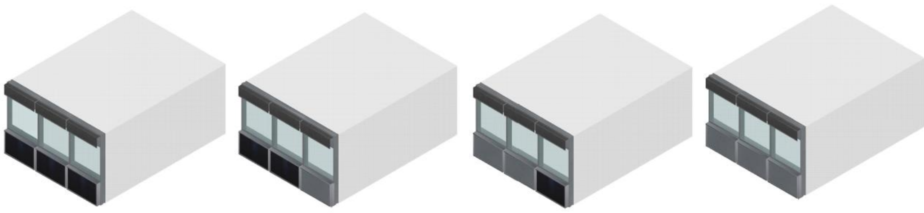


Figure 72 – Different façade compositions for the same office room typology (black panel indicates the solar thermal collector integrated into façade)

Three representative European locations were selected (London, Bolzano, Athens). For each location a specific insulation thickness was identified. Concerning the insulation glazing unit (IGU) system, six glazing systems were considered to give enough options to the tool user. Three Window to Wall Ratio values were set: 40%, 50%, 60%.

The office rooms with only passive façade modules required 216 simulations, deriving from the combination of three climates, three window to wall ratios, four façade orientations and six glazing systems.

Almost 2,000 simulations are necessary to complete the database, as showed in Table 29. Not all the configurations have been simulated, but the instrument's database is predisposed to insert results associated to each scenario as a string of values.

Table 29 – Number of simulations relative to the active façade scenarios

	Number of simulations	
Variables	South, East, West façade	North Façade
Location	3	3
Orientation	3	1
WWR	3	3
IGU	6	6
STarea	3	-
Numb STCs	1	-
Active area configurations	4	1
Total	1944	54

The office room façade is divided in three portions corresponding to three adjacent façade modules. In case one, two, or all the three modules are active and integrate the three hydraulic components, an average temperature of the façade deriving from COMSOL analyses is given to the active façade portion by means of *Data Reader* Type implemented in TRNSYS. Figure 73 shows the diagram of the energy model.

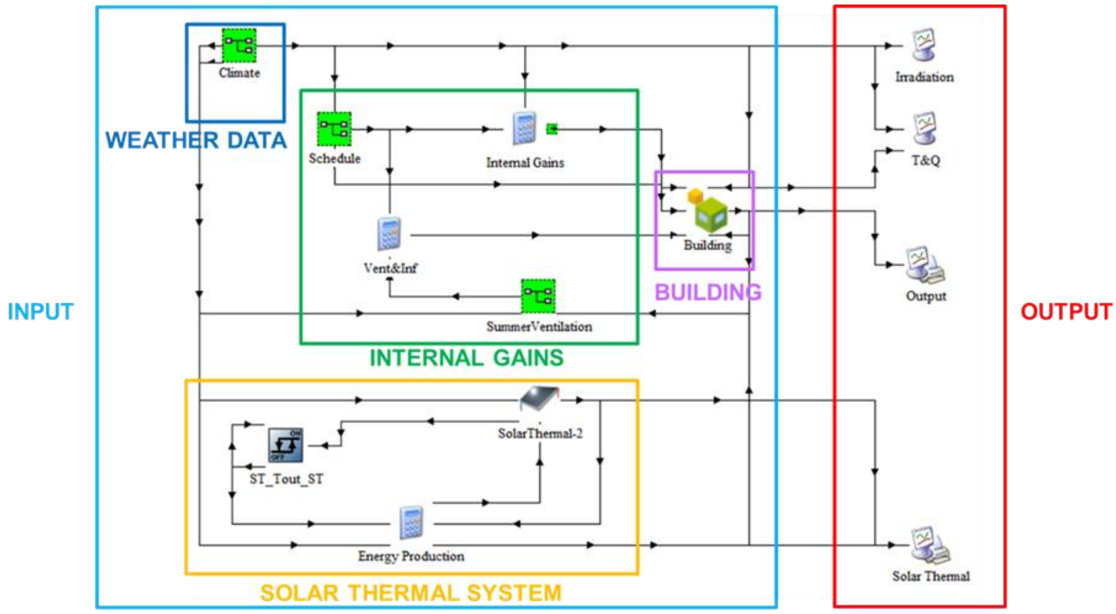


Figure 73 – TRNSYS model graphic interface

From this model the obtainable outcomes are:

- *Heating demand [kWh/m²y]*
- *Cooling demand [kWh/m²y]*
- *Heating peak power [W/m²]*
- *Cooling peak power [W/m²]*
- *Thermal comfort over occupation time [PMV>0.5 & PMV<0.5]*

The model allowed to calculate the energy demand taking into account the thermal exchange occurring inside the façade. On the one hand, the inwards heat flux contributes to lower the heating demand, but on the other one, the cooling demand is negatively affected.

After having calculated the energy demand as affected from the solar thermal façade in the different façade configurations and orientations, the produced thermal energy (obtained with the model showed in the paragraph 4.2.3) was post-processed and analyzed over the year, hour by hour. This evaluation was necessary to understand when the produced energy is needed due to heating space and domestic how water requests and when is cumulated and used indirectly in another moment according to the building needs. The not used energy, which becomes evident during summer, was just quantified but no thoughts about the potential use were done.

4.4 Façade prototype and design of experiment

Within *Sun-RISE* project, a prototype of the façade case study was built by the manufacture Stahlbau Pichler. Test activities to investigate the thermal performance of the façade system are part of the project. EURAC's Institute for Renewable Energy is provided with a test facility, called INTENT, to characterize the thermal performance of building envelope elements, either in dynamic or static mode. The laboratory is equipped with:

- *a double chamber with a guard-ring (the Guarded Hot-Box) built in accordance with standards UNI EN ISO 8990 and UNI EN ISO 12567-1;*
- *a solar simulator with lamps that emulate solar radiation;*
- *an external hydraulic circuit for evaluating the energy performance of hydraulic systems integrated in building components;*
- *a detailed monitoring system of sensors and data acquisition instruments that measure significant physical parameters with the aim of determining the characteristics of the test sample.*

When conducting the tests, the specimen is inserted into a frame located between the two climate chambers (the hot chamber and the cold chamber) that simulate interior air conditions (a hot box consisting of a guard box and a measurement box) and exterior air conditions by controlling the temperature, humidity and air velocity. The solar simulator reproduces the irradiation conditions on the external surface of the test sample while the hydraulic circuit controls any active hydraulic system integrated in the sample. The laboratory tests standard elements in accordance with the requirements of standard UNI EN ISO 8990 [106].

The aperture of the rear-side panel of the cold-box and the solar lamps permit the evaluation of the energy performance and thermal properties of active envelope elements with solar systems, in both static and dynamic modes. The hydraulic circuit can be used to calculate the heat absorbed by the active element as well as the heat removed or delivered throughout systems embedded in the construction element. For testing activated building systems (radiant wall/ceiling/floor systems), connection to an external hydraulic circuit and local measurements of heat flows allow the evaluation of the static and dynamic yield performances of the element.

The unitized façade subject to tests is 2143 mm wide and 2880 mm high. Usually façades are 1500 mm wide, while the height is between 3200 mm and 4000 mm depending on the floor-to-floor height. In this case, two aspects impose façade sizes: the height of the test facility and the width of the solar thermal collector. Indeed, the frame where the façade specimen is installed allows to test elements with a maximum height of 3120 mm (**Error! Reference source not found.**). In order to ease the installation of the specimen, it is better having a reduced size, but also realistic dimensions to avoid a scaling of effects. On the other hand, the façade dimension was dictated by the width of the solar thermal collector. Standard STCs have a 1000x2000 mm size; to avoid additional costs to create a special product, it was decided to adapt the façade to the STC's width.

Seven main elements define the façade system. The list of elements and suppliers of materials are here reported:

- *Aluminum profiles and façade frame (assembly by Stahlbau Pichler)*
- *Insulating glazing unit*
- *Radiant panel (by Hatek)*
- *Storage system (by Pink GmbH)*

- *Solar thermal collector (by Ökotech)*
- *Raffstore/shading system (by Warema)*
- *Hydraulic system (pipes, valves, pump) (by plumber and EURAC)*

Figure 74 – Active façade elements: solar thermal collector, storage system, radiant panel (front view)

Stahlbau Pichler carried out the assembly of the elements to produce the façade. Concerning the hydraulic part, a plumber was involved to develop and install the hydraulic box and the pipes running through the façade. Figure 75 shows the assembly of the aluminum profiles inside the factory.

Figure 75 – Assembly of aluminum profiles in workshop [October 2016]

The characterization of single components was not among the aims of the experimental activity. Indeed, the whole façade thermal performance was assessed. Metrics directly investigated through tests were:

- *Façade thermal transmittance with elements not activated*

- *The surface condensation risk, especially on the inner side*
- *The time to load the storage system before sending warm/hot water to the radiant system or to the centralized energy system (charging phase)*
- *The discharge phase of the storage system due to heat losses*
- *The heat transfer towards the hot chamber to understand the contribute/load reducing/increasing the energy demand*
- *The efficiency of the storage system by measuring heat losses both inwards and outwards*
- *Pipes surface temperature and mass flow rate*
- *Solar thermal collector's thermal power production*

Figure 76 shows INTENT facility and the façade prototype located within the frame that divides the two chambers. On the very right side, it is represented the solar simulator.

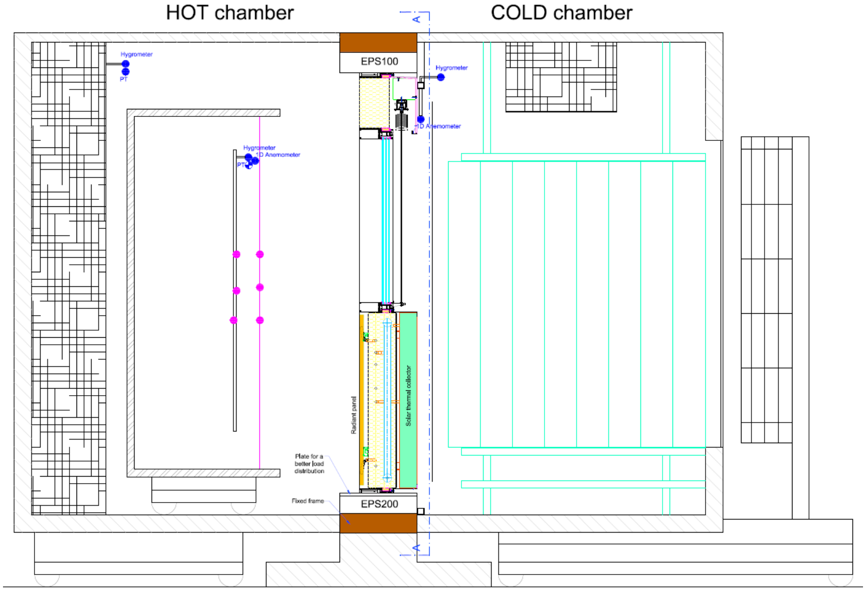


Figure 76 – Section of the façade specimen in INTENT lab facility

Figure 77 shows the façade prototype installed within the testing facility. In order to assess the heat flux perpendicular to the façade plan, an EPS insulation frame is necessary, in such a way that lateral heat losses are minimized. The façade lies on wooden sheets for a better distribution of the load. Holes drilled in side façade aluminum profile, allowing tubes to connect the façade to the centralized energy system or to another façade module, are visible in the below pictures.

Figure 77 – Façade prototype installed within the INTENT frame: external side. The empty space around the specimen is filled with EPS blocks

Two main hydraulic circuits can be identified into the façade system: the solar collector-storage (STC-S) circuit and the storage-radiant circuit (S-R). The first circuit involves the solar thermal collector, the storage system and the external circuit; this configuration is useful to quantify the efficiency of the storage and the inwards heat flux contributing to decrease/increase the energy demand when the radiant panel is not activated (similarly to the 1D thermal analysis showed in paragraph 4.2). The potential capacity of the fluid to remove the heat cumulated into façade during hot summer days was also investigated. Finally, the efficiency of the air gap between storage and STC was assessed. The second circuit encompasses the storage system, the radiant panel and the external hydraulic circuit; in this case, the influence of heat fluxes from the storage on the radiant panel operation was examined.

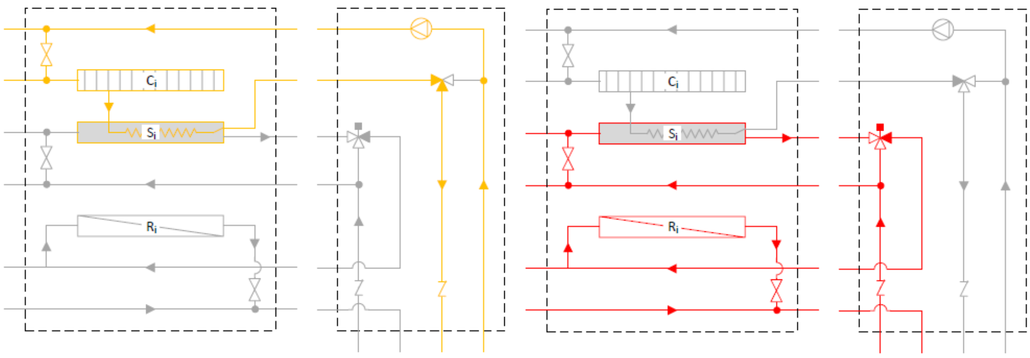


Figure 78 – Façade hydraulic circuits_STC-S to the left and S-R to the right

The auxiliary 2D model, showed in paragraph 4.2, can be validated through measurements acquired in laboratory. This model can be improved to get reliable data from FEM analyses and to assess the:

- *Façade thermal transmittance ($U_{façade}$-value)*
- *Thermal bridges*
- *Thermal discomfort associated to surface temperatures*

A constraint of the test activities regarded the use of the solar lamps to consider appropriately the optical/thermal effects of the façade. Indeed, solar lamps cannot hit in a homogeneous way the whole façade surface area. Aside from this aspect, it was decided to go for the tests with solar radiation anyway, but limited to the active façade area. This aspect is paramount to simulate the control system activating the solar pump integrated into façade, allowing the circulation of the warm water produced by the solar thermal collector. The load and discharge behavior of the storage system was examined in this way (STC-S circuit). Meantime heat fluxes both towards outside and inside were measured by means of heat flux meter plates.

Once a specific water temperature inside the storage is achieved, the solar heating function can be investigated by delivering the warm water to the radiant system (S-R circuit). To test the efficiency of the energy façade system, the hot chamber air temperature is initially kept to 15°C. Air temperature should increase gradually and it is quantified how much auxiliary heating is necessary, if any. The solar radiation simulator is also used to investigate the potential stagnation risk by taking off the solar pump.

The solar hot water production is evaluated starting from fixed temperature conditions inside the façade, especially into the water storage. By varying the solar radiation hitting the STC, the potential production is quantified. On the other hand, the same circuit can be used to assess how much time is needed to remove heat from the façade (STC-S circuit). This is possible by supplying chilled water; different water supply temperatures (15°C – 30°C – 45°C) are considered. In a building, this heat should be collected in a centralized water storage or delivered somewhere else (for example to other buildings through a district heating system). In laboratory, the hydraulic circuit is provided with a 200-l storage, hence it can be assumed as small, centralized system.

Finally, to other operation modes are verified: auxiliary heating and cooling functions. A constant mass flow rate is used, but different values of supply water temperature are implemented. These tests do not want to assess the amount of energy necessary to reach a certain room temperature, but the aim is checking the thermostatic control by assigning temperature ramps, in such a way to recreate activation and deactivation of the thermostat.

Since the solar radiation does not reach the entire façade surface, some effects due to irradiance are not triggered. For example, the convective-radiative exchange determined by a different temperature. For this reason, an overlapping of the effects from both measurements and simulation results should be carried out to assess the real performance of the whole façade.

To carry out the measurement campaign, many sensors are necessary. The list of sensors and a short description are reported in Table 30.

Table 30 – Sensors used to carry out the measurements

Name	Sensor type	Description
Thermocouples PT100	Temperature sensor	Electrical device consisting of two different conductors forming electrical junctions at differing temperatures. A thermocouple produces a temperature-dependent voltage as a result of the thermoelectric effect, and this voltage can be interpreted to measure temperature.
Heat flux meter plate	Thermal flux direction and magnitude	A transducer that generates an electrical signal proportional to the total heat rate applied to the surface of the sensor. The measured heat rate is divided by the surface area of the sensor to determine the heat flux.
Anemometer (omnidirectional)	Air velocity	A transducer with omnidirectional (spherical) sensor for measurement of air speed (magnitude of velocity vector) sensor. It measures are accurate and can detect air velocity in the range of 0.05 and 5 m/s.
Pipe temperature sensor	Temperature sensor	

Thermocouples are located on both visible surfaces and hidden parts as showed in Figure 79. Heat flux meters are small plates (120x120 mm) positioned on both the sides of the shell to measure the thermal flux going inwards and outwards from the storage system. Two small anemometers are placed inside the air cavity between shell and the radiant panel: air is expected to move due to convection favored by the heat flux coming from the storage. This metric is used to validate the fluid dynamic implemented in the 2D façade model.

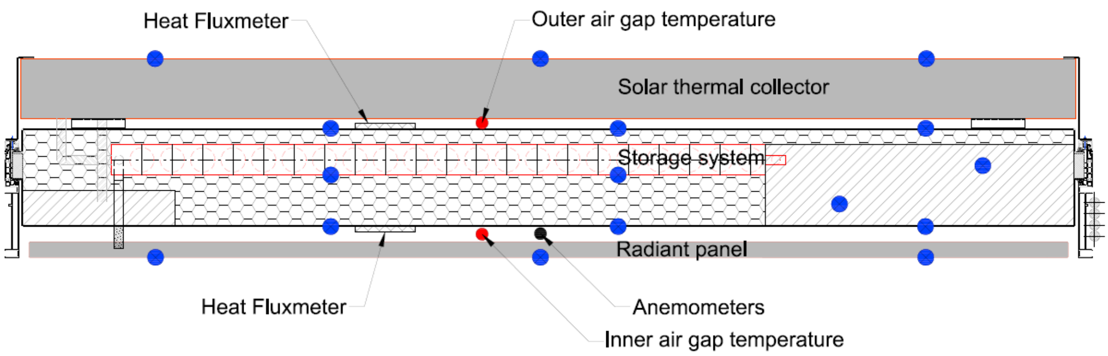


Figure 79 - Façade prototype_Sensors position_Horizontal section

Both the air cavities of the façade, between the aluminum shell and the external active elements, are provided with three sensors to measure the air temperature in the gap. These measures will help to define the potential convective flow, which is measured only inside the internal cavity by means of two anemometers. Four thermocouples are embedded in the aluminum shell: two between façade insulation and water storage, and two measuring the air inside the hydraulic box. Six thermocouples are applied to the external sides of the shell to trace a temperature trend inside the façade stratigraphy during the different tests. The acquisition of temperatures could also give an idea of potential issues connected to high-temperature failures.

The tests were launched on December 2016. The experimental campaign was performed until the end of the February 2017. Unfortunately, there was no time to analyze the collected data and use them to validate the façade models.

Chapter 5

5 FAST-IN tool: a simplified instrument to assess the business concept of solar façades

The final chapter of the thesis illustrates FAST-IN, the tool developed during the research program to bridge the gap in communication between façade stakeholders during the early design stage. FAST-IN stands for Feasibility Assessment of Solar Technologies INtegration. Aim of the tool is connecting the three backbones supporting the business concept for active façades (economics, technology, energy performance). The instrument implements several data allowing both designers and façade manufacturers to assess solar façade concepts with a relatively fast approach. Passive and active façade systems can be compared in terms of cost analysis, cash flows over time, energy performance.

Keywords: pre-design tool; decisions support process; envelope scenarios

5.1 Behind the tool

Product developers rarely explain clearly the costs associated to the components/systems they are selling. When it comes to innovative solutions, one of the most feared questions regards the initial cost and the economics over time due to maintenance, substitution or failures. The investment cost linked to a single technology is easily quantifiable but operation and maintenance costs are somehow in the dark. As long as the product developer or designer cannot show the advantages of the technology over time, it is doubtful that this can achieve the enough readiness to access the market. The tool illustrated in this chapter is an original instrument allowing designers, façade builders and investors to assess the incidence of several scenarios in terms of technology and maintenance. Technologies refer to façade solutions and energy system components. One can hypothesize the lifespan and the maintenance recurrence of these elements in order to evaluate the cost of each scenario over the building lifetime, and not stopping the analysis to the construction works. A user-friendly graphic interface has been thought to give answer to the gap in communication between façade stakeholders and to quickly investigate the potential linked to new façade concepts.

The idea of developing an instrument to assess different façade concepts and related energy systems grew out within the European-commissioned project FP7 Sinfonia [98], where Eurac is involved as coordinator. The embryonic version of FAST-IN tool finds here its origins. The goal was evaluating the impact of prefabricated timber-based façade elements as retrofit solution for a residential building. This scenario was compared with standard envelope renovation solutions to assess benefits and constraints in terms of installation time, costs, maintenance and energy performances. Although it was not yet FAST-IN tool, it can be considered the first application, which gave the author a first chance to define a structure, later improved.

Technical data of façade systems should give an impression of how good is the façade concept in terms of performances. Synthetic indicators should be associated to every façade system, regardless the complexity, depending on the climatic zone, the façade exposure, the façade configuration (transparent-to-opaque ratio) and the building use. These four characteristics are among the most influential in the performance characterization of envelope systems. One of the intents of FAST-IN tool is providing performance indicators related to active façade solutions according to dynamic calculations. The excel spreadsheet has been arranged focusing on the solar thermal façades, their energy performance and influence on the office comfort and energy needs. However, different solutions in terms of façade and energy system can be implemented and investigated. Some indicators like acoustic, fire safety and static requirements are not considered, even though a comprehensive work should include these aspects as well.

The methodology used to assess the performance of the façade case study solution starts from office room scale. Since the tool was thought to assess a façade case study integrating a solar thermal collector, the first sheet allows the user to configure the main features of a Solar Thermal Façade: Window to wall ration, glazing system, solar thermal technology and active area per façade module. Even though a lower degree of detail applied, other façade solutions can be implemented. Indeed, external thermal insulation, passive curtain walls and BIPV façades can be assessed as well. The idea is providing a kind of datasheet for each office room, depending on properties characterizing the façade system. Several simulations were carried out to populate a database of results. Different orientations, WWR, façade configurations were implemented in a model; these rooms can be then used to configure a virtual building with as many 'cubes' as specified by the user in order to be assessed as a whole in terms of economics and feasibility of the intervention.

The tool is structured in seven sheets, linked one to each other to consider many of the aspects that should be assessed in the early design stage. Actually, the first sheet just allows to move quickly to the desired page and it could be considered the *sheet zero*. Here follows a description of the 6 following sheets included in the excel file. To link the structure of the FAST-IN tool to the business scheme illustrated in Figure 9, for each sheet a table lists the required INPUT (specifying whether they are filled in manually or automatically from pre-set calculations) and the obtainable OUTPUT subdivided in TECHNOLOGY, ECONOMICS and PERFORMANCE groups.

TOOL (1st sheet)

Main goals of the first sheet are:

- *showing to users potential benefits of solar technology integration into façade at office room scale*
- *comparing energy performances between two different energy concepts*

The sheet includes four macro areas:

- *Façade Module Configuration*
- *Building Façade Configuration*
- *Photovoltaic Installation*
- *Results*

Specifications in the tool can be visualized in two languages: English and Italian. Once the language has been defined, the user can choose the location among few European cities to consider different climate conditions. Solar radiation in particular. So far only one building use typology has been implemented: the office building. However, other cases can be inserted in the future.

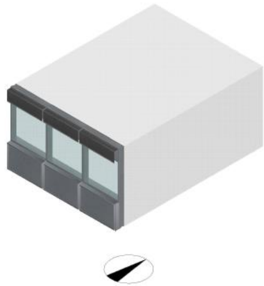
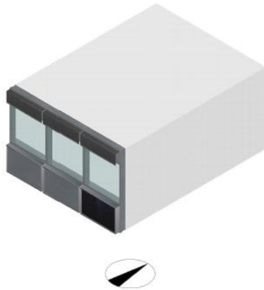
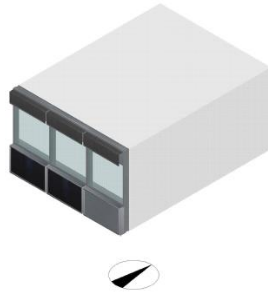
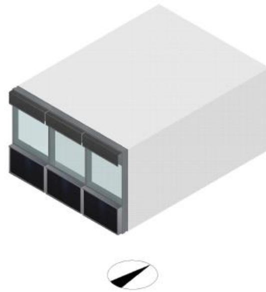
Energy model's features are listed in the first part of the sheet, more in detail room's dimensions, internal loads, envelope air tightness, insulation properties and façade modules sizes. Currently, this is a limit of the tool since only one reference room is implemented. Open space cannot be considered in this first version. Another limit of the instrument is the implementation of only one ST technology, the solar flat plate glazed collector. ST features used to simulate the façade energy performance are listed in the sheet. Unglazed collectors and vacuum tube collectors will be inserted in a future version. New simulations would be necessary if one wants to implement a new technology and consider the thermal effect of the integration. Otherwise, simple calculations can be done by neglecting the building physics, as it was done so far with photovoltaic technologies.

After the active façade module has been defined, it is possible to identify a potential financial support scheme leading to a first evaluation of the payback time of the extra-cost related to active technologies integrated into façade. The user can define a subsidy for Renewable Energy Sources integration expressed as percentage of the extra-cost or an increased value of the building compared to an average monthly rent. An annual maintenance cost incidence can also be fixed as a start to be applied at room scale. A clear maintenance plan in terms of costs and recurrence can be defined in a following step to have a better idea of the influence of the upkeep during the building life cycle. The eventual financial support scheme is better implementable in the sheet 2 *Technology Implementation*. The following step is the definition of the number of office rooms with a specific orientation and the number of floors of the building.

As discussed in chapter 3, two active façade concepts are investigated: the *solar thermal façade* and the *distributive façade*. The second concept integrates only the distribution pipes to feed the radiant system. At the moment, the tool is set in such a way to configure solar thermal façades and distributive façades as design scenario to be compared with other passive solutions or photovoltaic installations both on façade and on roof, which can be seen as competitive design solutions. The thermal effect of photovoltaic integration was not assessed. About the PV distribution on façade, the number of active façade modules is obtained by dividing the photovoltaic surface area by the available opaque portion area, which is supposed to be covered by PV panels.

An extract of the TOOL sheet is showed in Table 31. Four façade configurations are possible can be adopted for each orientation: three distributive façade modules; one solar thermal façade module + two distributive façade modules; two solar thermal façade modules + one distributive façade module; three solar thermal façade modules. Performance indicators are listed for each façade solution. Office rooms have only one dispersing surface, that is the façade the user can configure, otherwise surfaced are adiabatic. This is an important assumption, since the ground floor and the top floor would have at least two non-adiabatic surfaces.

Table 31 – Office rooms with Performance Indicators (Bolzano, South façade, WWR 50%, new monthly rent)

Active façades / Exposed façade	No Active Solar Façade Modules 3 Active Distributive Façade Modules	1 Active Solar Façade Module 2 Active Distributive Façade Modules	2 Active Solar Façade Modules 1 Active Distributive Façade Module	3 Active Solar Façade Modules No Active Distributive Façade Modules
South				
Annual production of solar energy [kWh/y]	-	629.4	1258.8	1888.2
Heating demand [kWh/m²y]	40.4	39.6	38.8	38.0
Solar Fraction for Heating	-	11.2%	22.9%	35.1%
DHW demand [kWh/m²y]	4	4	4	4
Solar Fraction for DHW	-	43.8%	87.5%	100.0%
Cooling demand [kWh/m²y]	60.0	64.0	68.0	72.0
Heating peak power [W/m²]	120	110	100	95
Cooling peak power [W/m²]	105	110	120	140
Thermal comfort over occupation time [PMV>0.5 & PMV<0.5]	87.0%	85.0%	84.0%	83.0%
Daylight Autonomy	80.0%	80.0%	80.0%	80.0%
Extra-cost [€/m² façade]	246.6	300.5	354.4	407.8
Extra-cost Payback Time [years]	8	10	11	12

The choice of the different rooms leads to a virtual office building. The graphic effect of the building might be the one showed in Figure 80, nut it cannot be visualized into the tool. Obviously, the final performance takes into account the indicators associated to each room. The selected performance indicators were:

- *Annual production of solar energy from the façade [kWh/y]*
- *Heating demand [kWh/m²y]*
- *Solar Fraction for Heating*
- *DHW demand [kWh/m²y]*
- *Solar Fraction for DHW*
- *Cooling demand [kWh/m²y]*
- *Heating peak power [W/m²]*
- *Cooling peak power [W/m²]*
- *Thermal comfort over occupation time [PMV>0.5 & PMV<0.5]*
- *Daylight Autonomy*
- *Extra-cost [€/m² façade]*
- *Extra-cost Payback Time [years]*

Daylight Autonomy is implemented to take into account the effect of glazing-integrated technologies like photovoltaic, not yet selectable among the technologies. For this reason, this indicator depends only on façade orientation, glazing system and WWR, which are features valid for every façade system.

The *Extra-cost* is referred to a reference case provided with passive façade modules and a standard energy system providing warm/cool air with fancoil units. The façade case study substitutes the fancoil unit thanks to the integrated radiant panel. Other installations that can be assessed are photovoltaic panels on façade or roof. The tool is also predisposed to assess solar thermal systems on roof.

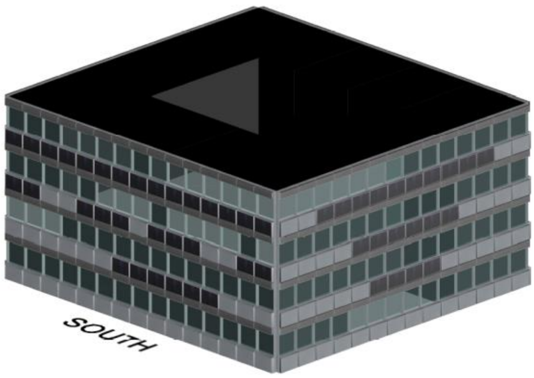


Figure 80 – Example of virtual office building obtained by joining more office rooms

Beyond technical costs and material procurement, the façade extra cost can takes into account the associated risks as evaluated in the paragraph 3.2. In case of a first application, the lack in know-how increases the investment cost. This can be varied from the user in another tool sheet later explained. Upkeep costs, operation costs (pumps) and space cooling load over time are implemented as well. On the other hand, savings due to uninstalled energy distribution systems (e.g. fan coil units), the related saved energy and other items are taken into account.

The *Extra-cost Payback Time* is calculated by considering cost savings and extra-costs over time, but potential RES integration contributes and building extra-value (through the increase of the monthly rent, for example) can be implemented.

Here follow the phases that brought to the calculation of the key performance indicators for each scenario:

1. *A single-zone energy model was implemented in TRNSYS energy modelling environment. The model reflects a reference office room with dimensions and internal loads deriving from other simulation experiences.*

Office and Envelope Features	Value	U.M.
Office Width	4.5	m
Office Height	3	m
Office Depth	6	m
Lighting Power Density	15	W/m²
Equipment Power Density	10	W/m²
Envelope air tightness (n50 value)	2	ACH
Shading system: Venetian blind with aluminum lamellae		
Shading system activation: if solar radiation on façade > 200 W/m²		
Insulation material	Mineral Wool	
Insulation thickness	10	cm
Curtain Wall Façade Width	1.5	m
Curtain Wall Façade Heigth	3	m

2. *Three representative European locations were selected (London, Bolzano, Athens) and three orientations (South, West, East) were considered for the implementation of both solar thermal façade modules and distributive façade modules. The North front is evaluated only for the passive façade (reference case) and the active distributive façade.*

For each location a specific insulation thickness was identified. Concerning the façade glazing system, the user can insert values of thermal transmittance (Ug), solar factor (g-value) and visible transmittance (VT) to identify an IGU with similar properties among six solutions. The glazing features are then used to recall from the database the energy performance of the rooms and the building.

3. *Three Window to Wall Ratio values were set: 40%, 50%, 60%.*
4. *The reference office room with passive façade modules was simulated: 216 simulations (3 climates, 3 WWR, 4 orientations, 6 glazing systems)*

It is necessary to stress the importance of the ratio of roof surface area to façade surface area, and the maximum available space on the roof, once the building dimensions are clear. Indeed, the presence of other installations like mechanical ventilation machines and the need of a solar thermal surface area proportional to the size of the building especially for mid to high-rise buildings are constraints that can limit this application.

5. *The office room scenarios obtained by combining the several technical specifications (WWR, active façade area, orientation, climates, IGU, …) were simulated as illustrated in paragraph 4.3.*
6. *Finally, the database was populated with results obtained from energy simulations.*

To summarize what is included in this sheet, Table 32 lists all the INPUT necessary to get results, not only included in this page but, also for other sheets' results. Under the INPUT_automatic column, it is specified if the input comes from dynamic calculations (DYN) or steady state calculations (STAT). One could also insert results from other simulations and change the geometry/envelope features with the ones used in the software. Automatically these new input would be recalled in the other sheets. One constraint in this sheet are the lack of graphics showing every implemented characteristic, for example the PV area coverage on both façade and roof, which is simply distributed on the envelope elements depending on the available opaque surface area. Otherwise, many degrees of freedom are left to the user.

Table 32 – Sheet 1_TOOL_INPUT and OUTPUT

	INPUT		OUTPUT
	Manual	Automatic	Automatic
Location	x		
Building typology	x		
Building & envelope systems (TECHNOLOGY)	Thermal transmittance	Office size	
	Solar factor	Façade Width	
	Visual transmittance	Façade Height	
	WWR	Glazing system	
	Solar thermal area to opaque area	Internal loads	
	Solar thermal technology	Shading system technology	
	Number of floors	Shading system control	
	Number of rooms	Insulation material	
	Number of active façade modules		
	Photovoltaic technology		
	% PV area on opaque façade area		
	% PV area on roof area		
	PV orientation on roof		
	PV tilt angle on roof		
	Self-consumed PV electricitiy		
Energy performance (PERFORMANCE)	DHW demand	Lighting demand at room level_DYN	Energy demand at building level_Design solution
		Equipment demand at room level _DYN	Energy demand at building level_Competitive solution
		Heating demand at room level _DYN	% lighting demand Design-to-Competitive ratio
		Cooling demand at room level _DYN	% heating demand Design-to-Competitive ratio
		Thermal energy production at room level _STAT	% cooling demand Design-to-Competitive ratio
		Comfort hours at room level _DYN	Produced thermal energy and solar fraction for SH and DHW
		Daylight at room level _DYN	Produced electricity and solar fraction for electical uses
		Electricity production_STAT	Power density at room level

		Thermal comfort for each orientation [PMV] Visual comfort for each orientation [illuminance from daylight]

Technology implementation (2nd sheet)

Main goals of this first sheet are:

- *defining the technologies to be implemented in the scenarios*
- *defining the financial and energy parameters to assess the Net Present Value of the investment*

Once the façade has been configured and the building size fixed, more details can be defined within the second sheet. Indeed, this page allows the user to specify technologies related to the building energy system, the building site equipment to install the façade system, the energy carrier for the different uses, the financial scheme and parameters varying the cash flow structure to calculate the net present value of the proposed envelope solution.

The first part of the sheet is mainly devoted to the implementation of equipment to carry out some construction works like installation of external thermal insulations panels (scaffolding) or prefabricated façade systems (crane and aerial platforms). A Yes/no filter determines if the technology item has to be considered in the building cost analysis. Different façade solutions can be selected: external thermal insulation, passive curtain walls, active façades (BIST, BIPV, Piping integration), new windows and shading systems in case of retrofit, window-opening sensors. When insulation is necessary (external thermal insulation for façade and roof) material and thickness can be specified by the user, while quantities are automatically calculated depending on other choices. ST and PV systems to be installed on roof can be implemented; for these items the solar technology can be selected. Finally, the HVAC components (mechanical ventilation, heating, cooling and domestic hot water systems) can be chosen by specifying the technologies and the number of units to be installed. For each technology a rough estimation of the number of days to carry out the construction works is reported.

In the second part of the sheet, the users points out the energy carrier for space heating, DHW, space cooling and specifies the energy systems efficiencies. In case of PV installations, it can be defined how much energy is sent to the energy grid, and as consequence the self-consumption rate.

The third section is related to the financial strategy to support the installation of active façade systems, including a payment plan and possible contributions. Economic parameters, necessary to calculate in an appropriate way the cash flows are also input that the user can define and assess their influence over time. Table 33 summarizes all of the items.

Table 33 - Sheet 2_Technology Implementation_INPUT and OUTPUT

	INPUT		OUTPUT
	Manual	Automatic	Automatic
Building & envelope systems (TECHNOLOGY)	Building site arrangement		Duration of works (Cash Flow Comparison sheet)
	Façade installations		
	Active technology integration		
	Windows replacement and glazing system		
	Shading system replacement		
	Roof installations		
	Seismic reinforcement		
	HVAC system		
	Lighting system retrofit		
Energy performance (PERFORMANCE)	Energy carrier for SH, SC, DHW	Space heating demand	Cash flow (Cash Flow Comparison sheet)
	Energy system efficiencies	SH coverage from RES	
	DHW coverage from RES	Space cooling demand	
	Electricity to the grid rate	Lighting demand	
	Natural Gas Calorific Power	Electricity production	
Financial scheme and economic parameters (ECONOMICS)	Third party fund/loan incidence	Total construction cost	Total cost of intervention (BUI Cost Analysis sheet)
	Third party fund/loan interest rate	Own investment	Cash flow (Cash Flow Comparison sheet)
	Third party fund/loan duration (1-10 y)	Third party fund/loan	
	Mortgage incidence	Mortgage	
	Mortgage interest rate	Incentive for RES integration	
	Mortgage duration (1-10 y)	New monthly rent	
	Subsidy for RES integration		
	Subsidy for RES duration (1-10 y)		
	Revaluation rate (rent increase)		
	Natural Gas Cost		
	Natural Gas Increase Rate		
	Electricity Cost		
	Electricity Price Increase Rate		
	Feed-in tariff for Photovoltaic installation		
	Discount Rate		

The total cost of intervention is showed in this page, but calculations from which this value derives are reported in the fourth sheet (Building Cost Analysis). The choices here implemented are a determining factor for the cash flow trend, summed up in the sixth sheet (Cash Flow Comparison). It has to be stressed that unitary costs associated to each item are recalled from a not visible sheet, except for the façade systems' cost, which represents a key element in this work.

Façade Costs Definition (3rd sheet)

Main goals of this first sheet are:

- *defining the cost of façade components to be recalled in the building cost analysis*

For each curtain wall façade system, the user can define the whole list of the components' cost, except for the active technologies for which the cost is fixed depending on the technology selected in the first two sheets. Concerning other envelope technologies, costs are automatically linked to the selected material (insulation material and glazing system).

Table 34 lists the façade components for which the user can insert a unitary cost manually, and those that are automatically filled. These choices affect the total façade cost, the building investment cost and the cash flow trend.

Table 34 – Façade Costs Definition_INPUT and OUTPUT

	INPUT		OUTPUT
	Manual	Automatic	Automatic
Component costs (ECONOMICS)	Façade anchoring system cost	Solar thermal collector	Façade cost
	Slab connection	IGU	Total cost of intervention (BUI Cost Analysis sheet)
	Upper façade panel	Radiant system	Cash flow (Cash Flow Comparison sheet)
	Hydraulic components&connections	Shading system	
	Shading system (raffstore)	Photovoltaic panel	
	Insulation		
	Façade frame		
	Production		
	Logistics		
	Engineering		

The tables showing the façade components of each façade technology are the ones showed in the paragraph **Error! Reference source not found.**.

<u>*Building Costs Analysis (4th sheet)*</u>

Main goals of this first sheet are:

- *getting a technical specifications draft list for envelope and energy-related items*
- *obtaining the cost of intervention for the selected construction works*

After having detailed the façade costs, all the elements necessary to have a building cost analysis are provided to the tool. The users must not insert any input since all the needed numbers (related to façade technologies surfaces area, material quantities and number of façade elements, number of energy system units, items' unitary costs and amounts) are automatically implemented as described in Table 35. Automatically, the tool displays the total cost of each construction work and the cost of intervention including also VAT, security charges and other technical expenditures not specified so far (design, acceptance tests). This page is set up in a way to obtain a rough list of tender specifications, which usually is better defined in a later design stage.

Table 35 - Building Cost Analysis_INPUT and OUTPUT

	INPUT		OUTPUT
	Manual	Automatic	Automatic
Quantities (TECHNOLOGY)		Façade technologies surface areas Quantities of material, elements Energy system units	
Component costs (ECONOMICS)		Unitary cost's items Amount	Total cost of intervention for selected components Cash flow (Cash Flow Comparison sheet) Tender specifications (simplified form)

Maintenance (5th sheet)

Main goals of this first sheet are:

- *planning a maintenance plan over the building lifetime for façade and energy systems aspects*
- *assessing the incidence of specific choices in terms of costs and maintenance recurrence on the Net Present Value*

One of the main objectives of the tool is the evaluation of the maintenance of active technologies integrated into façade, which increases the amount of money needed to guarantee the building performance over time. The user can configure a sort of maintenance plan and assess its influence on the cash flow trend during the first 50 years of life of the building. In order to do this, several input can be modified manually to give as much freedom as possible to the user. Table 36 sums up inputs included in the sheet and the main outputs affected by the choices.

Table 36 - Maintenance_INPUT and OUTPUT

	INPUT		OUTPUT
	Manual	Automatic	Automatic
Quantities (TECHNOLOGY)	Components' lifespan Cleaning/Maintenance recurrence among some choices		Maintenance plan over 50 years Cash flow (Cash Flow Comparison sheet)
Component costs (ECONOMICS)	Cost for removal and substitution of components Cost for cleaning/inspection of components		

The sheet gives the user the chance to adjust parameters related to building components' lifespan (end of life and necessary removal/substitution) and ordinary maintenance over time. Regarding the components' life, years can be defined and costs for removing/disposal and installation of a new component/system. About the ordinary maintenance, the user can establish the cleaning/inspection recurrence among some possible scenarios (1 to 3 years for some components requiring often an inspection or 5, 10, 15 years for active technologies packages). Table 37 shows the items demanding maintenance and a possible way to determine the cost at the end of life of the components. Potential sources for costs are pointed out. For the cleaning/inspection matter, the method to consider costs and the recurrence definable by the user are specified as well.

Table 37 - Maintenance_Assumptions on End of Life cycle and Maintenance costs and recurrence

Item	Lifespan/End of life	Source/notes	Cleaning/Inspection	Source/notes
IGU	Cost for removal + new glazing + installation	Façade manufactures	Cost per m² (every 1 to 3 years)	Façade maintenance handbook. Cost should include personnel and equipment.
Insulation	Cost for removal + new installation	Commercial analysis	-	
Raffstore	Cost for removal + new system + installation	Façade manufactures	-	
STC on façade	Cost for new supply and installation per m² active surface area*1.05	3 to 5% increase of installation cost can be assumed to consider removal and disposal. Façade manufacturers and BIST producer could be inquired.	Cost per m² (every 1 to 3 years)	BIST producer
Electronics/Controls	Forfait per façade module		Cost per façade module (every 1 to 3 years)	
Storage	Cost for new supply and installation per façade module *1.05			
Radiant system	Cost for new supply and installation per façade module*1.05		Cost per façade module (every 5 or 10 or 15 years)	5% of active components in façade defined in Sheet3.
Valves	Cost for new supply and installation per façade module*1.05			
Pumps				
Ducts	Forfait cost per façade			
PV panel on façade	Cost for new supply and installation per m² active surface area *1.05	Façade manufacturers and BIPV producer could be inquired.	Cost per m² (every 1 to 3 years)	BIPV producer
Battery	Cost per façade module			
Inverter	Cost per façade module		Cost per façade module (every 5 or 10 or 15 3 years)	5% of active components in façade defined in Sheet3.
Charge controller	Cost per façade module			
STC on roof	Cost for new supply and installation per m² active surface area *1.05	STS producer could be inquired.	Cost per m² (every 1 to 3 years)	STS producer
Valves	Cost for new supply and installation per m² active surface area			
Pumps			Forfait per year (every 5 or 10 or 15 years)	STS producer
Ducts	Cost for new supply and installation per m² active surface area			
PV panel	Cost for new supply and installation*1.05	PVS producer could be inquired.	Cost per m² (every 1 to 3 years)	PV producer
Battery	Cost per kWp			
Inverter	Cost per kWp		Forfait per kWp (every 5 or 10 or 15 years)	PVS producer
Charge controller	Cost per kWp			
Fancoil unit	Cost for new supply and installation*1.05		Cost per unit (every 1 to 3 years)	http://www.edwardsvalance.com

Boiler + centralized storage + distribution	Cost for new building system and installation*1.05		Cost per building (every 1 to 3 years)	
Pumps Valves	Forfait for a centralized energy system (medium office building)	3 to 5% increase of installation cost can be assumed to consider removal and disposal. Energy systems producers could be inquired.	Cost per building (every 1 to 3 years)	
Mechanical ventilation_Decent	Cost for new MV system and installation*1.05		Cost per office room (every 1 to 3 years)	3 to 5% of new installation cost
Mechanical ventilation_Cent	Cost for new MV and installation*1.05		Cost per office room (every 1 to 3 years)	
Chiller + distribution	Cost for a new building system and installation*1.05		Cost per building (every 1 to 3 years)	

Starting from the year of construction to 50 years (minimum building life expectance), the yearly maintenance cost is implemented in the cash flow analysis, which is not visible to the user. However, the incidence of maintenance costs on the net present value is reported in the final sheet as cumulated value every 5 years.

Cash Flow Comparison (6^{th} sheet)

Main goals of this first sheet are:

- *comparing the main economics of the two implemented technology scenarios*
- *deciding the best solution*

The last FAST-IN tool's sheet does not require any manual input from the user. The showed data are simply recalled from other pages. Total days to carry out the selected construction works, main technical costs and total intervention cost are reported to summarize a few information. The output of this sheet is the comparison of net present value (NPV) of the design scenario and the competitive solution 'built' through the tool's pages. The NPV is reported every five years from the beginning to 35 years of building lifetime, and maintenance discounting back is showed as well with same frequency to get an impression of how much impacts the cash flow over time. Table 38 lists input and output included in the sheet.

Table 38 – Cash Flow Comparison_INPUT and OUTPUT

	INPUT		OUTPUT
	Manual	Automatic	Automatic
Contrusction works duration (TECHNOLOGY)		Days needed for energy-related items	
Main variable costs and NPV (ECONOMICS)		Merged technical costs Intervention cost	Incidence of technical costs on the total investment Net Present Value over 35 years of the 2 set scenarios Maintenance discounting back

The author considers the insertion of pictures representing the tool sheets something not useful to the reader. For this reason only input, assumptions, choices flexibility and outputs have been described. An example of application is reported in the next paragraph for helping to understand better the use of the tool and the comparison between the implementation of the solar thermal façade case study and a reference case with a standard façade solution (passive façade).

5.2 Assessing the affordability of a solar thermal façade

As mentioned in the dissertation, an office room thermal zone with a width equal to three façade modules was taken as basic model to develop the tool presented in the paragraph 5.1. Depending on the number of solar thermal façade modules, series connections characterize the link between active components. Every office room has a decentralized energy system. Besides single rooms, office buildings can be provided with another internal configuration, consisting in bigger spaces called *open spaces.* With this room typology, longer series might be plausible but open spaces were not considered in the simulations.

This paragraph shows two examples of application of the tool and a sensitivity analysis of the results by varying economic parameters like the cost of the energy over time (increase/decrease rate by assuming this rate is constant along the years) and the discount back rate to analyse the cash flows over time. The results inserted in the tool's database can be easily modified to update or add values and make it a better instrument. This application test has the main goal to evaluate the easiness of use and the efficiency of the output to provide information to the user.

Since there is not a real case study for the application, it is assumed that the building is a new construction managed by a real estate agency interested to finance an active envelope solution. Two technology scenarios are compared to assess which solution is better from the performance and economic point of view. One solution considers solar thermal façade modules as part of the building envelope; more specifically a façade including an energy concept similar to the one developed for the case study has been considered (solar thermal collectors, a thermal storage not specified in terms of technology and a radiant panel as inner surface). The other portion of the envelope (that is bigger than the solar thermal façade) is considered as distributive, that is passive modules with a radiant panel to provide heating and cooling to the office rooms. Two solutions were compared with this scenario. One represents a standard building scenario with passive façade modules and energy distribution by means of fancoil units (1 per office room), while the other one is an active façade solution implementing photovoltaic panels coupled with a heat pump generating thermal energy to produce both heating and cooling. Domestic hot water is also assumed to be covered by the heat pump. Shown below is reported the description of the scenarios. Either the scenarios refer to an office building with 40 office rooms distributed on two floors. For each orientation and floor, five office zones are implemented. The building is located in Bolzano, Italy.

Scenario 1 – Solar Thermal Façade (STF)

Façade technology: Solar Thermal Façade Modules + Distributive Façade Modules

WWR: 50%

Glazing technology features: Ug= 1.1 W/m²K; g= 0.55; LT= 0.63

Active façade modules: 20 south-oriented modules for a total active surface area of 30 m² (the solar thermal collector covers the entire opaque surface area portion beneath the glazed surface)

Solar Thermal Technology: Flat Plate Glazed Collector

Auxiliary heating energy system: Centralized Boiler + Water Storage

Auxiliary cooling energy system: Chiller + Radiant panels integrated into façade

Number of office rooms per floor: 20 (5 for each orientation)

Number of floors: 2

Scenario 2 – Passive Façade (PF)

Façade technology: Passive Façade Modules

WWR: 50%

Glazing technology features: Ug= 1.1 W/m²K; g= 0.55; LT= 0.63

Auxiliary heating energy system: Centralized Boiler + Water Storage + Fancoil units

Auxiliary cooling energy system: Chiller + Fancoil units (1 unit per office room)

Number of offices per floor: 20 (5 for each orientation)

Number of floors: 2

Scenario 3 – Photovoltaic Façade (PVF)

Façade technology: Photovoltaic Façade Modules (polycrystalline modules) + Passive Façade Modules

WWR: 50%

Glazing technology features: Ug= 1.1 W/m²K; g= 0.55; LT= 0.63

Active façade modules: 13 south-oriented and 12 east-oriented modules for a total active surface area of 42 m² (it was assumed the photovoltaic surface area covers the opaque façade panel beneath the glazed surface of the modules)

Auxiliary heating energy system: Centralized Heat Pump (water-to-air) + Water Storage + Fancoil units

Auxiliary cooling energy system: Centralized Heat Pump (water-to-air) + Fancoil units (1 unit per office room)

Number of offices per floor: 20 (5 for each orientation)

Number of floors: 2

The features reported above are specified in the first sheet of the tool. In the second sheet, the user implements all the necessary technologies to create the list of construction works for the specific scenario.

All of the façade scenarios feature curtain wall systems. Assuming the unitized façade technology, a mobile crane and one aerial platform should be enough to carry out the construction works. Scaffoldings are not needed.

Concerning roof installations, the insulation can be implemented, but in this analysis focusing on the façade and the energy system, this aspect is not considered. Energy systems features are highlighted here below.

- *Heating energy carrier: natural gas or electricity depending on the scenario*
- *Boiler efficiency (heating generation system): 0.90*
- *Heat pump water-to-air efficiency (heating and cooling generation system): variable depending on condenser and evaporator temperatures*
- *DHW energy carrier: natural gas for Scenario 1 and electricity for Scenarios 2 and 3*
- *Chiller COP (cooling generation system): 3*

The real estate manager has enough availability of money to build the building, regardless the façade concept. However, the agency wants to optimize the operation and maintenance costs over the building lifespan (50 years). Due to an energy program supporting the integration of Renewable Energy Sources based technologies on building envelope, the real estate can benefit from a local government contribution covering 50% of the costs of active envelope systems. The grant is paid back in 5 years.

Besides these contributions, the building manager can opt to apply a monthly rent higher than the average office buildings rent. The following analysis shows the sensitivity of some parameters, which can determine the effectiveness of an investment.

Economic parameters to analyze the cash flows over time are the same for the two scenarios:

- *Natural Gas Calorific Power: 9.96 kWh/m³*
- *Natural Gas Cost: 0.8 €/m³*
- *Natural Gas Cost Increase Rate: 1.0%/year*
- *Electricity Cost: 0.22 €/kWh]*
- *Electricity Price Increase Rate: 1.0%/year*
- *Discount Rate: 2.0%/year*
- *Feed-in tariff for energy produced from photovoltaics: 0.00 €*

The user can specify all these parameters.

Following the FAST-IN tool structure, the user has to define the façade solutions cost. The final costs per square meter are listed in Table 39. The cost composition is reported in paragraph 3.4.

Table 39 – Façade systems cost as defined in the sheet3 of FAST-IN tool

FAÇADE SYSTEM	FAÇADE COST [€/m²]
PASSIVE FAÇADE_BOLZANO	625
ACTIVE DISTRIBUTIVE THERMAL FAÇADE	833
ACTIVE SOLAR THERMAL FAÇADE_BOLZANO	963
ACTIVE SOLAR PV FAÇADE_BOLZANO	933

The following subparagraphs focus on the comparison among the three scenarios briefly introduced: the Solar Thermal façade + centralized boiler and storage + chiller (ST); the Passive Façade + fancoil units + centralized boiler and storage + chiller (PF); the Photovoltaic façade + fancoil units + heat pump for heating and cooling.

5.2.1 Solar Thermal Façade (STF) scenario and Passive Façade (PF) scenario

Depending on the input given in the sheet2, surfaces related to envelope solutions are automatically calculated and showed in the sheet4 as reported in Table 40. In this example of application, only south-exposed offices were chosen to install solar thermal collectors for a 30 m² active surface area. The rest of the façade modules integrates the radiant panel, avoiding the installation of fancoil units.

Table 40 – Envelope solutions and surface areas for each scenario

Envelope items per each Façade scenario	STF	PF	PVF	U.M.
Total External Thermal Insulation façade area	0	0	0	m^2
Solar thermal façade modules (supplying and installation)	90	0	0	m^2
Distributive façade modules (supplying and installation)	450	0	0	m^2
Solar PV façade modules (supplying and installation)	0	0	119	m^2
Passive façade modules (supplying and installation)	0	540	421	m^2
Glazing	270	270	270	m^2
Shading system	270	270	270	m^2
Insulation on ROOF	0	0	0	m^2
PV on ROOF	0	0	0	m^2
ST on ROOF	0	0	0	m^2

The cost analysis ends up with a prospect of the costs involved for the construction works limited to the items specified within the tool. Obviously, this is not a comprehensive cost analysis since structures, floors and other works are not included.

Table 41 – Summary of the initial cost for each scenario

	STF	PF	
Total cost of intervention (w/o VAT and security charges)	675,000	552,000	€
Total cost of intervention for m^2 floor area	**625**	**511**	**€/m^2**
Total cost of intervention for m^2 façade area	**1250**	**1022**	**€/m^2**

If the analysis were to be stopped here, the investor and maybe the designer of the façade as well, would push for the solution implementing the passive façade modules. This tool finds its originality in the evaluation of the future economics. As already stressed, the user can go into detail of the future costs to be paid and set the maintenance plan associated to façades and energy systems, so that the assessment of the scenarios is based on energy and economic performance and it becomes more complete.

The choices made in the first sheet have determined automatically a coverage rate of the demand for space heating and domestic hot water. The solar thermal façade scenario allows to cover 9.1% of the demand thanks to the solar heating loop and the heat stored during the days when it is not directly used; it is important to stress that the inwards heat flux during the heating season, reduces the heating demand, bringing to a more favorable scenario. Since the demand is very low, domestic hot water is almost completely covered, while a higher cooling demand is achieved in comparison with the passive façade scenario.

Within the first sheet of the instrument (TOOL), some results are displayed and plotted in charts. Energy demand and production are summarized for each month at building scale. Energy demand is divided in heating, cooling, domestic hot water, equipment, and lighting. The produced thermal and electricity are also showed, depending on the technologies implemented. The percentage of demand covered through renewable energy over the year is also reported. Figure 82 shows the bar chart with all the energy demands for the proposed design solution and it compares the lighting, heating, cooling demand between the design solution and the alternative scenario.

Another interesting output is the comparison between the two solutions in terms power of needed for heating and cooling over the corresponding season. This outcome is reported for each office room exposure and façade configuration and it is reported as percentage relative to the peak power simulated for the reference rooms. Figure 81 shows this outcome for the south-exposed office room having 2 solar thermal façade modules and 1 distributive façade module. The chart reports the frequency distribution of both heating and cooling power. Even if noticeable differences cannot be detected, it is clear that the heating peak power is reduced by integrating the solar thermal collectors and the entire energy concept into façade, while the cooling peak power is increased.

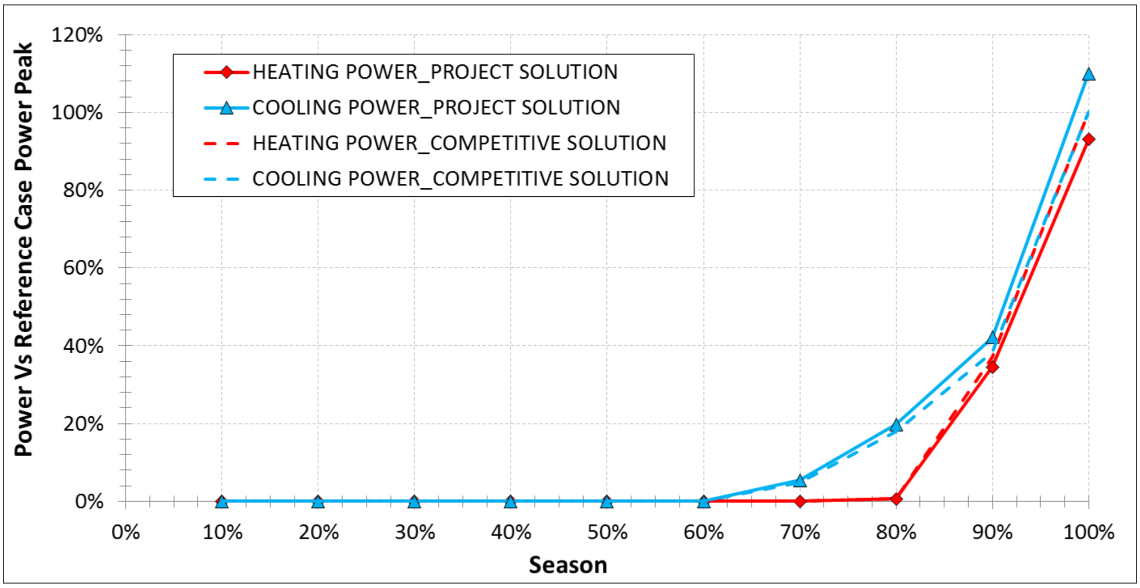


Figure 81 – STF Versus PF_Heating and cooling power frequency distribution of design solution (solid line) and competitive solution (dashed line)_South-exposed office with 2 solar thermal façade modules

Regarding energy aspects, two other outcomes are reported in FAST-IN tool. The yearly thermal comfort during the offices occupation time is showed for each façade orientation. The metric used to assess thermal comfort is the Predicted Mean Vote, and comfort is achieved if this metric is included in a range between -0.5 and 0.5. The other performance indicator the user can visualize concerns the illuminance in the office room. The daylight autonomy is used as metric to assess this indicator. It shows the percentage of hours where the minimum required illuminance (500 lux for offices) is achieved only through natural daylight. Obviously, if the window to wall ratio and the glazing type are the same for both the solutions, the results are the same. This comparison gives an idea of the achievable value of daylight autonomy, and it can be more interesting when standard glazing systems are compared with photovoltaic integrated into glass panes for example.

In the fifth sheet of the tool, components' lifespan and costs for their removal and substitution were fixed as reported in Table 42. Regarding the regular maintenance/inspection/cleaning of components, the recurrence and costs were defined as well. With this page, the user can easily assess what happens if a different frequency of maintenance is fixed.

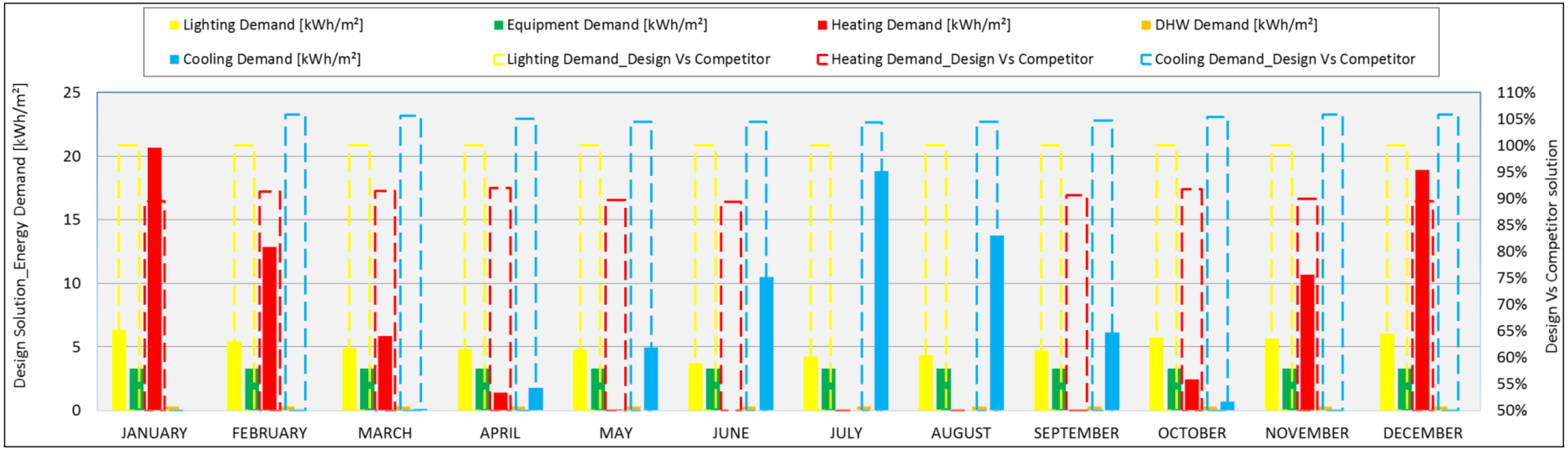


Figure 82 – Energy demand for the different uses (design scenario) and comparison to the alternative solution (dashed bars)

Table 42 – ST Versus PF_Maintenance and substitution plan

System	Component	Lifespan	COST [€]	U.M.	Cleaning/Inspection	COST [€]	U.M.
FAÇADE	IGU	20	170	m²	2	5	m²
	Insulation	30	120	m²	-	-	m²
	Raffstore	25	320	m²	-	-	m²
SOLAR THERMAL FA-ÇADE	Solar thermal collector	20	210	m²	2	3	m²
	Electronics/controls	10	100	façade module	1	0	façade module
	Storage	30	378	façade module	5	5%	façade module
	Radiant system	30	189	façade module			
	Valves	20	158	façade module			
	Pumps						
	Ducts	20	50	façade module			
DISTRIBUTIVE FA-ÇADE	Radiant system	30	189	façade module	10	5%	façade module
	Ducts	20	100	façade module			
PV FAÇADE	PV panel	25	416	m²	1	3	m²
	Battery	7	100	façade module	5	5%	façade module
	Inverter	10	50	façade module			
	Charge controller	10	50	façade module			
ST ROOF	Solar thermal collector	20	210	m²	1	3	m²
	Valves	20	50	m² ST	5	100	forfait/year
	Pumps						
	Ducts	20	50	m² ST			
PV ROOF	PV panel	25	378	m²	1	2.5	m²
	Battery	7	500	kWp	5	500	forfait/kWel
	Inverter	10	250	kWp			
	Charge controller	10	250	kWp			
ENERGY SYSTEM	Fancoil unit	15	630	unit	1	50	unit
	Boiler + Centralized storage	20	36750	building	1	1750	building
	Pumps	20	2000	building	2	100	building
	Valves						
	Mechanical ventilation_Decent	15	3150	office room	1	150	office room
	Mechanical ventilation_Cent	15	2625	office room	1	125	office room
	Chiller	15	31500	building	2	1500	building

The final sheet allows to compare the net present value (NPV) achievable over time. A chart like the one showed in Figure 82 is reported in the tool. The chart shows the initial investment and the NPV every five years. The analysis is not just focused on the extra costs between the two scenarios, but it considers all the construction works selected. According to the implemented technologies and the relative costs, it can be observed that the initial cost of the solar thermal façade scenario is almost 125,000 € more expensive than the standard solution. No incentives for RES-based technologies or re-evaluations of the building through an increased rent have been implemented at this stage. An 1% incremental variation for natural gas and electricity costs was hypothesized, while a 2% discount back rate is used to calculate the NPV. The discounted back values' gap narrows with time.

Another aspect emphasized in the chart is the maintenance over time, pointed out by the two solid bars overlapping the total costs (light blue bars). Values have to be read on the right axis. The standard solution implements fancoil units, demanding a bigger annual expense for inspection and components' change. The cash flows trend shows that costs to be faced for the Solar Thermal Façade (STF) scenario are lower than the costs related to the Passive Façade (PF) solution. Maintenance for the ST scenario is more onerous when the solar thermal system requires the substitution with a new one as reported after 20 years.

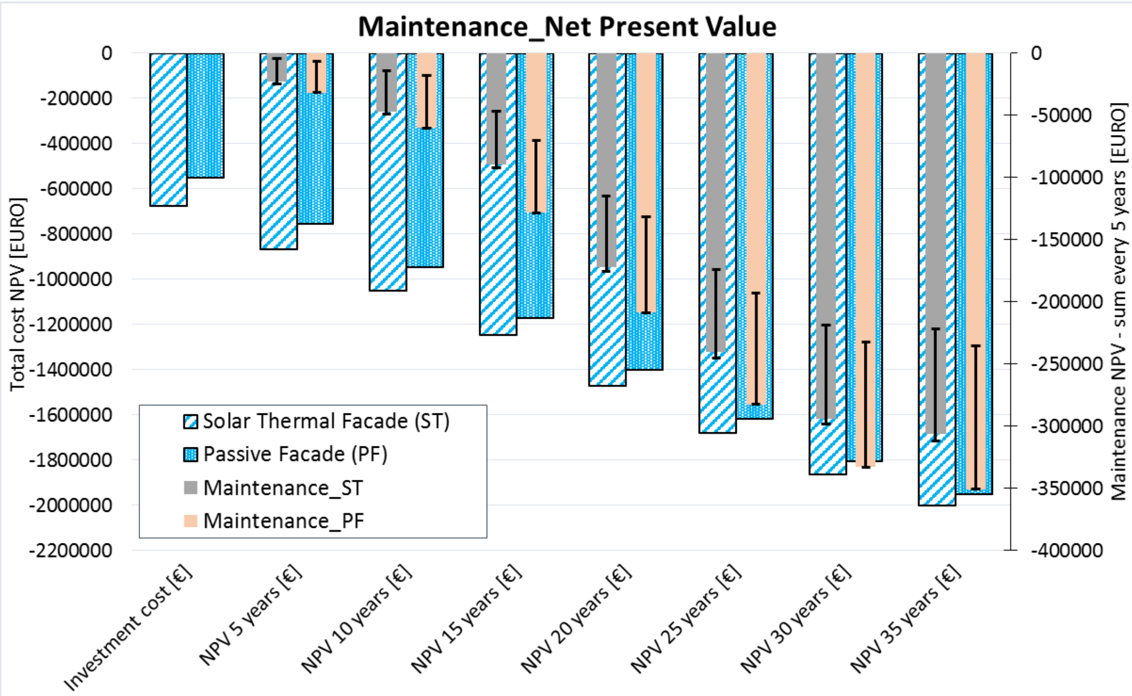


Figure 82 – STF Versus PF_Net Present Value for the two analyzed scenarios and maintenance cash flow every five years (error bars refer to frequent/rare maintenance)

The error bars represented over the maintenance costs bars identify the range of costs depending on the frequency of inspection, cleaning and substitution. For the case of the solar thermal façade 90,000 € can be saved after 35 years if a low maintenance level is preferred to a frequent one. That way, failures could be more likely to occur and lifespan of components reduced, bringing actually to a reverse situation.

The variation of some economic parameters can disrupt the cash flows trend showed in the above chart. The following figures display the net present value per square meter of floor surface area. The chart displayed in Figure 83 compares four scenarios: two related to the STF case (grey lines) and two linked to the PF case (black lines). This first analysis focuses on the effect of:

the yearly variation of natural gas cost (Δgas); the yearly variation of electricity gas cost (Δelect); the discount rate (Disc). The number following the initials is the implemented value. It is reasonable thinking that these parameters vary in the same way regardless the scenario. For this reason, both the design solutions have the same economic scenarios.

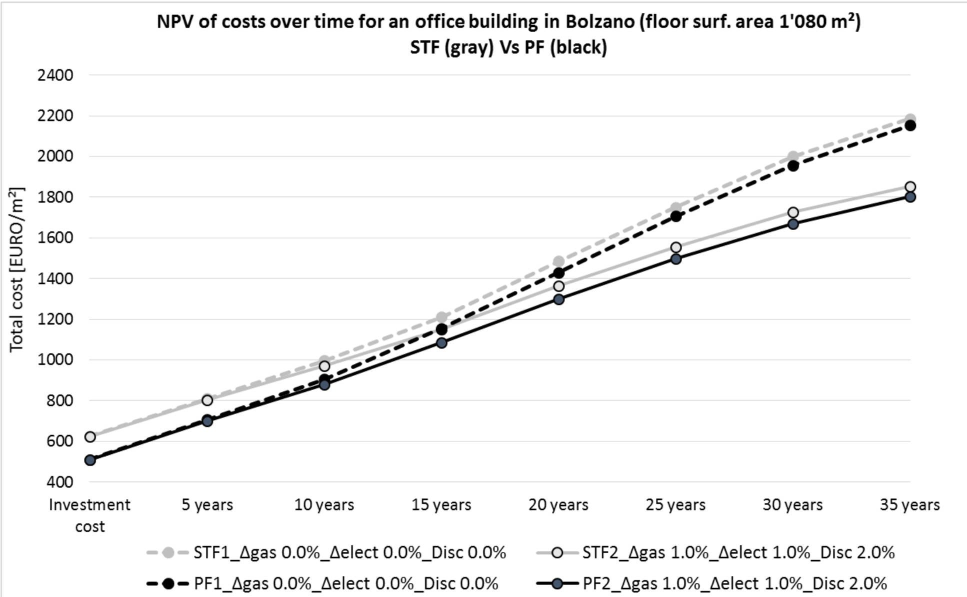


Figure 83 – STF Versus PF_NPV trend depending on energy costs increase and discount back rate

If all of the three parameters are set to zero, the delta cost after 35 years is 30 €/m² in favor of the passive façade scenario, while the initial cost differs 114 €/m². A similar difference is obtained if parameters are set at 1% as yearly energy cost variation and 2% as discount back rate, but net present values are lower. A closer analysis of the net present value of the two building configurations is possible within the tool framework. The bar-graph reported in Figure 84 highlights the differences of NPV over time respect to a STF reference scenario with no energy cost variation and no discount back rate. Differences between the two building configurations are the same as the two solid lines reported in the previous chart.

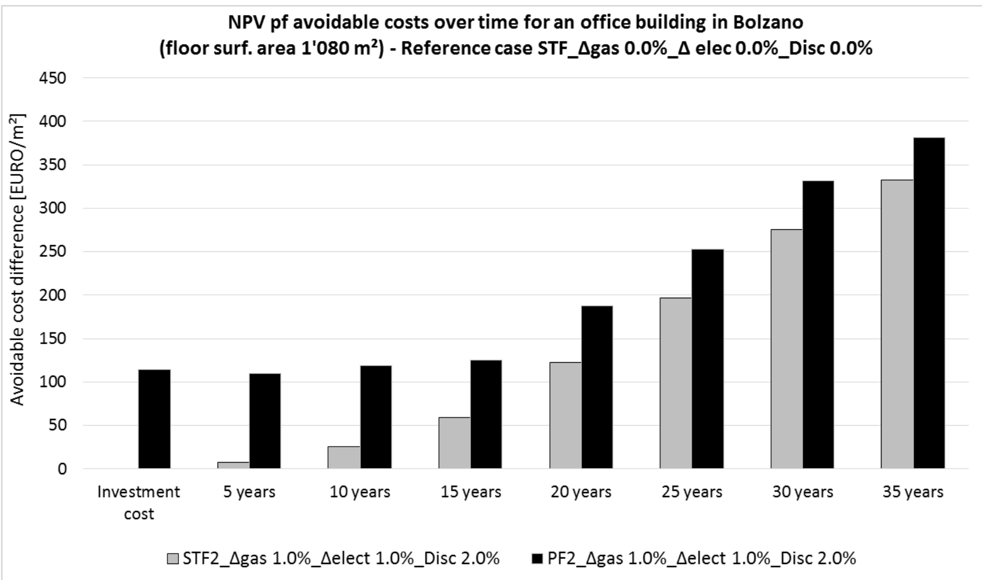


Figure 84 - STF Versus PF_NPV difference depending on energy costs increase and discount back rate

The comparison of economic scenarios become more interesting if other parameters more sensible to the technology solutions are implemented. Figure 85 shows a chart similar to the previous one, but three different parameters are investigated. Differences are more evident. This time, the variation involves the RES subsidy for solar active technologies (RES); the rent fee increase rate (Rent); the tariff foreseen for sending the produced energy from PV plants to the local grid (PV). The number following the initials is the implemented value. With regard to the last parameter, the PV feed-in tariff, a similar scheme could be considered for solar thermal systems if extra energy could be put into local district heating networks. Since this is not a practice, such an option is not included within the tool.

Energy cost increase rates and discount back rate are fixed. The dashed lines lead to the same trend traced by the solid lines in Figure 83 since no incomes are considered. Concerning the STF case, a RES subsidy covering 50% of the cost related to the solar thermal façades was inserted and a 20% increased rent fee (basic rent 5 €/m²/month) was implemented; finally no energy feed-in tariff was fixed. Passive façades cannot benefit from a RES contribute, while a 10% higher rent fee was considered. The bigger rent increase for the STF case can derive from the use of radiant panels, which do not occupy space and avoid air movement due to convection (higher indoor air quality).

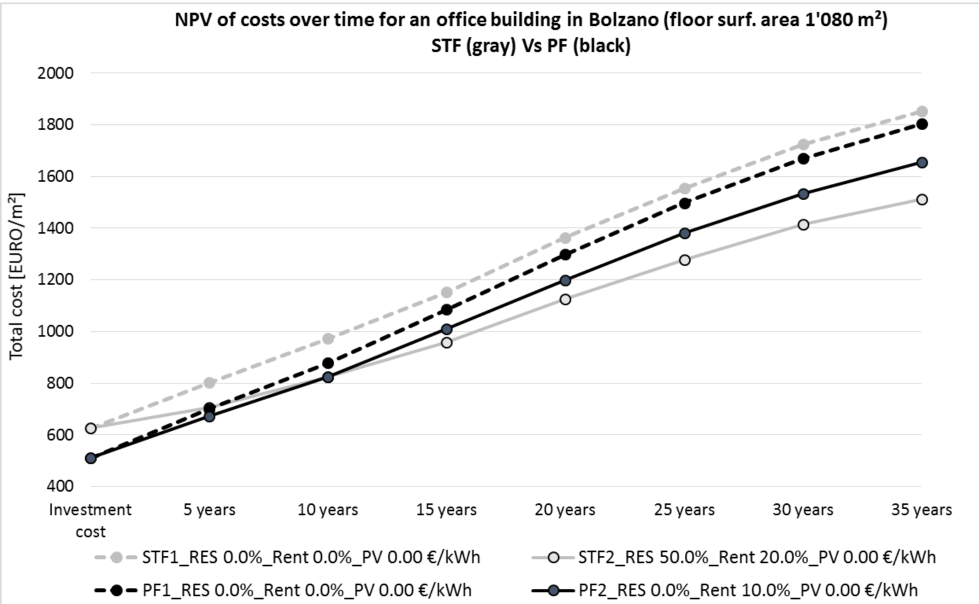


Figure 85 - STF Versus PF_NPV trend depending on RES subsidy, Rent increase rate, Energy feed-in tariff

Focusing on these two scenarios (solid lines), the needed costs equalize after 10 years and the STF case becomes more profitable over time, always considering energy and maintenance costs. Similarly as for the previous analysis, the avoided costs, due this time to potential incomes, are reported in Figure 86. The reference case is the solar thermal façade case with no incomes. Despite the initial important difference between STF and PF case, both the solution lead to an avoidable cost of 150 €/m² after 10 years, but after that period the gap increases in favor of the solar thermal façade configuration, reaching almost 150 €/m² at the 35th year from the initial investment.

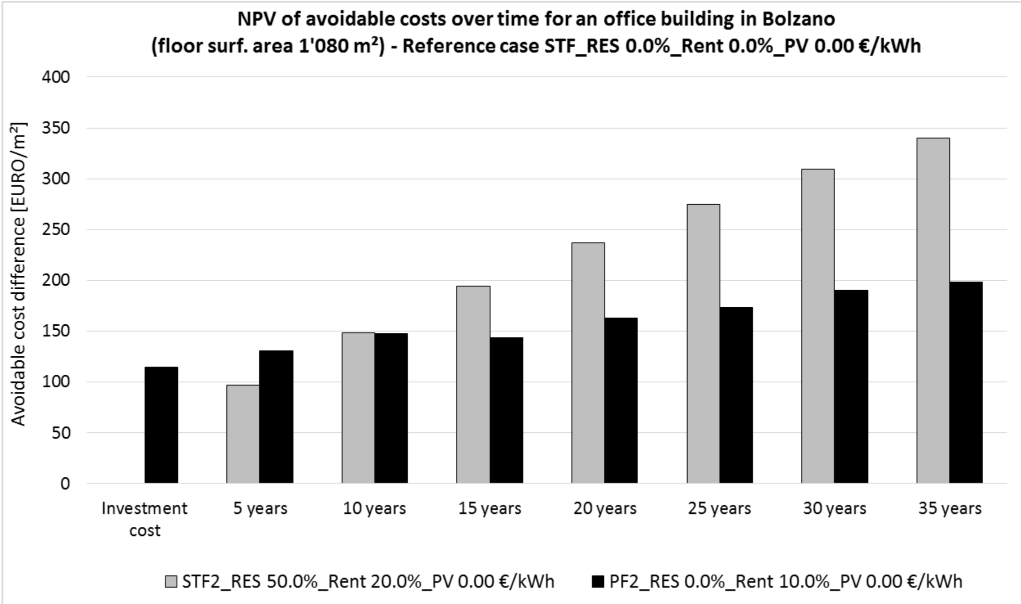


Figure 86 - STF Versus PF_NPV difference depending on RES subsidy and rent increase rate

This application showed primarily the potential of the tool in comparing different economic scenarios within the same design solution and between two different façade-energy system configurations. Several economic scenarios are pre-calculated and they can be easily recalled and displayed by typing the acronyms as illustrated for the above charts. On the other hand, it was presented the comparison of two façade solutions, one active and one passive. This kind of evaluation necessarily requires the implementation of the energy systems. Under several economic assumptions (necessary to analyze the business concept of active façade systems), it was demonstrated that solar thermal façades can be competitive, but it seems that incomes (due to subsidies, building re-evaluation, feed-in tariff) are necessary to support active façade concepts. The cost reduction of solar thermal façades linked to material procurements and façade production is likely to happen only if several applications are expected, as it happened for the photovoltaic technologies.

Regarding the reading of the charts, a negative NPV (or increasing cost trend) was evidenced. Indeed, including all of the construction works in the cash flow analysis has as a consequence a not favorable investment. At least, it can be visualized the year when the two investments would lead to the same NPV. The author of this thesis decided to compare the technology solutions in absolute terms, considering all the investment related to the building envelope and the energy system.

5.2.2 Solar Thermal Façade (STF) scenario and Photovoltaic Façade (PVF) scenario

In the previous subparagraph, a comparison between an active and a passive façade was illustrated; a second comparison of façade solutions was analyzed. In this case, two active façade concepts were simulated: a system similar to the façade case study (BIST) and a Building Integrated Photovoltaic (BIPV) façade. This comparison makes more sense since two energy-delivery technologies are identified as competitive solutions. The ST scenario is the one already introduced during the first evaluation: the solar thermal loop is localized on the façade of different south-exposed office rooms and a centralized energy system works as back-up for heating and cooling sending warm or cold water to the radiant panels installed in each office. The PVF concept is thought to be coupled to a water-to-air heat pump generating thermal energy for both heating and cooling. The amount of photovoltaic panels was defined considering the same solar fraction for space heating and domestic hot water from renewable energy sources obtained with the ST concepts. The implemented solution conceived the use of 50% available opaque façade surface area on the south front and 45% of the east prospect. 42 m² of photovoltaic surface area where considered. In terms of façade modules, 13 active modules where supposed to be installed oriented to south and 12 on the east side.

To estimate the production of electricity from the photovoltaic surface, a simple TRNSYS model was created. Type 94a was used to calculate the production of energy according to a specific azimuth angle and slope of the surface. The inverter efficiency was considered by means of an equation linked to the production output from Type 94a.

$$eff\_inverter = 1-(0.04252*(P_{out}/P_{nom}))-exp(-12.02*(P_{out}/P_{nom})\text{^}(0.4725))$$

where:

P_{out} is the power obtained in output from Type 94a

P_{nom} is the nominal power of the PV module

No energy storage system (battery) was considered; hence, the not used electricity is sent to the grid and a feed-in tariff can be defined for each kWh. This value can be specified by the tool user; as first assessment no feed-in tariff was inserted. The Italian legislation and supporting scheme (Scambio sul posto) currently foresees a 0.14 €/kWh tariff.

For each façade orientation and for each month, the solar yield per square meter of PV surface area was calculated as for the ST surface area. Likewise to what was performed for the solar thermal façade, the electricity produced was evaluated hour by hour and compared with energy needs over the year. Differently from a solar thermal façade, within this scenario the produced energy can be easily used even during summer thanks to the heat pump load to generate cooling. It was assumed that the coupling between photovoltaic façade and heat pump is a pure coupling; hence, the only load covered from the photovoltaic system is the one linked to the heat pump, if this energy generation system is selected. Other loads like lighting and appliances were not considered in this case. If heat pump is not selected as energy system, but other solutions like the chiller, are implemented, a self-consumption rate is considered according to a user specification. In this case, the overall electrical load is considered as coupled with the PV system.

The implementation of the two scenarios required a continuous tool fine-tuning in order to guarantee a minimum flexibility of the instrument in considering different façade and energy systems solutions.

The energy system should be sized according to the energy required from back-up systems (boilers, chillers, heat pumps). The tool does not consider this aspect. For a small office building like the one used as example, the impact of the size of energy systems on the overall economics is not relevant. However, for medium to big buildings it might be not so negligible.

Figure 87 shows only a part of the chart related to the energy demand that the user can visualize within the tool. Focusing on the month of January, the red solid bar quantifies the space heating demand of the solar thermal façade scenario, while the yellow and the green bars are related to lighting and equipment demand, respectively. The dashed bars show the energy demand relative to the photovoltaic façade solution. The values have to be read on the right vertical axis. For example, the space heating demand is 95% the one characterizing the building with BIPV façades or 5% less. This phenomena occurs thanks to the inwards heat flux generated inside the solar thermal façade. Moving the attention on August, the light blue solid bar points out the space cooling energy demand; in this case the dashed bar is higher than 100%, meaning that the space cooling demand is higher in comparison with the PVF solution. Once again, the heat flux generated into the façade going inwards changes the energy need of the building, increasing this time the cooling load. Lighting demand is the same for both the scenarios since the same glazing system is considered in terms of dimensions and glass panes.

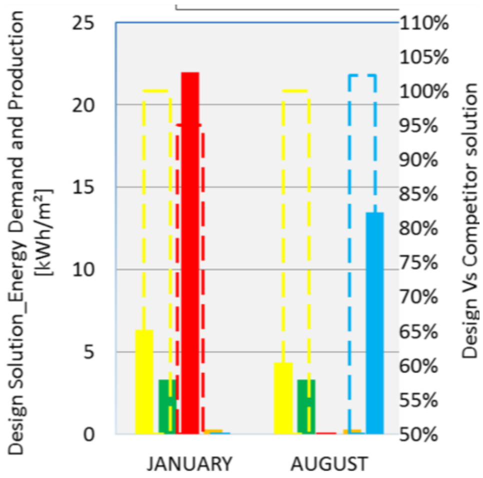


Figure 87 – Energy demand for the different uses_absolute values (solid bars) for the STF scenario and values comparative to PVF solution (dashed bars)

Since two active envelope solutions are compared, the energy production over the year and its use are paramount to assess how good is one solution compared to another one. Figure 88 compares the solar fractions for space heating+DHW and cooling, and the rate of energy produced and used to cover energy needs. Solid lines refer to the BIST façade and dashed lines to the BIPV façade scenario. Concerning space heating and domestic hot water, the solar fraction (red lines) is similar; even though differences from April to October are visible. Indeed, during the warm months only the DHW demand is present (except for a few days during mid seasons) and despite of the difference in percentage (April), the absolute value of the energy produced and used for thermal needs is the same over the year for the two scenarios. The thermal storage charge/discharge behavior was not implemented. The solar thermal façade cannot produce energy to be used for cooling purposes. That is why a flat line is reported in the chart (light blue solid line). Differently, the PVF partially covers the cooling demand from March to October. The higher solar fraction during March, April and October is due to low cooling loads. Green lines point out how much of the produced energy is used over the year; from October to March the trend is equal, while a clear advantage in using the photovoltaic façade coupled with a heat pump emerges from April to September, reaching a peak during July (85 %). The not used energy share is sent to the local grid. For the Solar Thermal Façade configuration, the not used energy can be stored in the centralized water storage or flowed into a low-temperature district heating loop. Compared to the energy produced from solar thermal collectors and directly used inside the building, the photovoltaic scenario leads to a 55% higher use of the produced energy, corresponding to the integral of the difference of the areas between green dashed and solid lines, as highlighted in Figure 89.

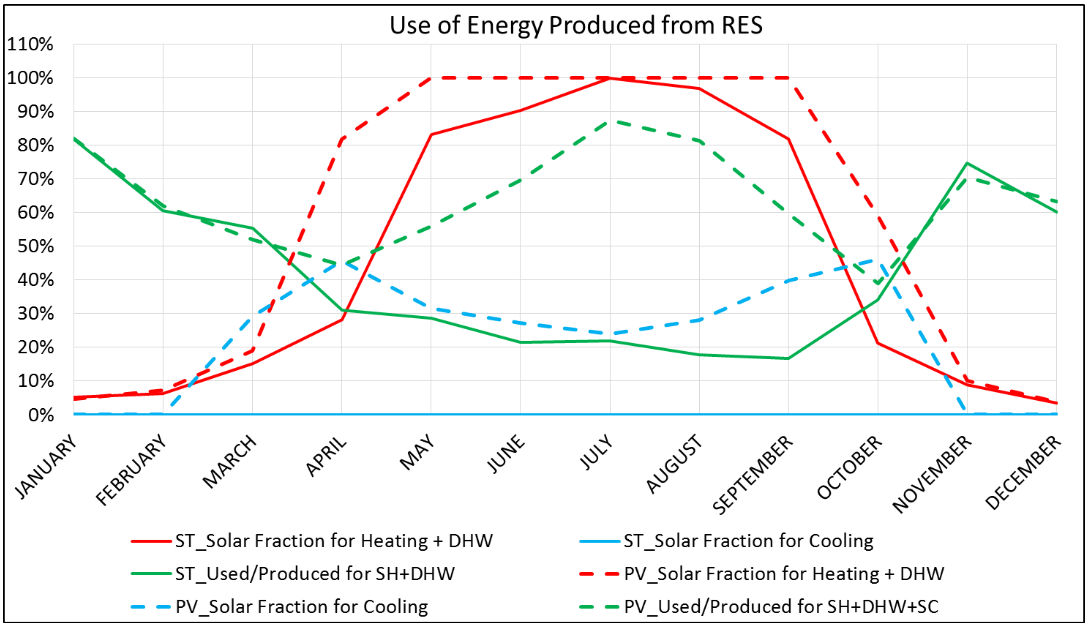


Figure 88 - STF Versus PVF_Energy produced and solar fraction (Bolzano)

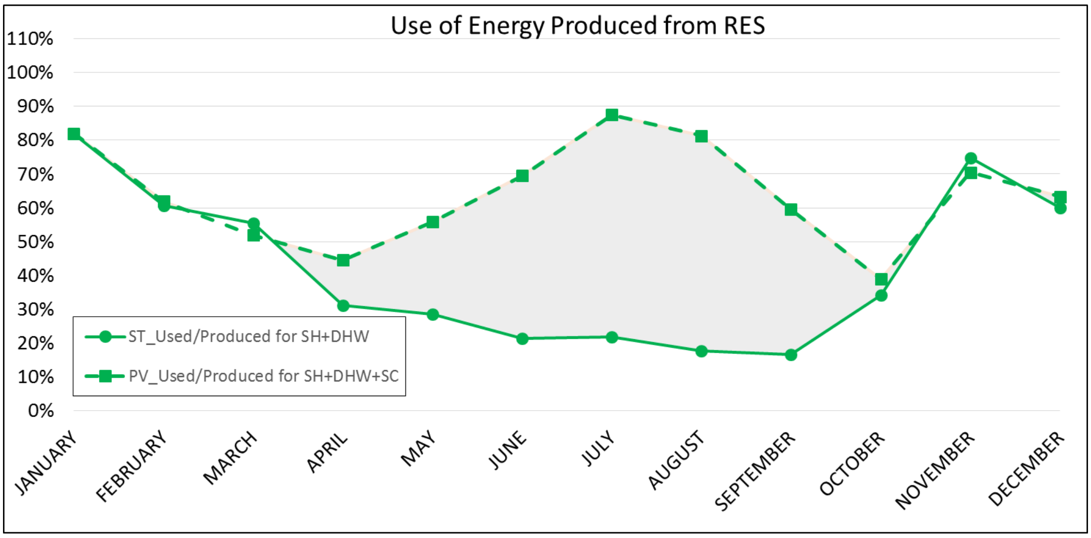


Figure 89 - STF Versus PVF_Energy self-consumption rate over the year (Bolzano)

The energy output was assessed also for the city of Stockholm (Sweden) considering the same building. The same STF case (30 m² solar thermal collectors south oriented on façade) was implemented. To achieve the STF solar fraction for space heating and DHW, a photovoltaic surface area of 20 m² south oriented is required in Stockholm, hence an amount lower than half the one needed in Bolzano. This surface is equivalent to 45% the opaque surface of the south façade. Once again an advantage in installing PV technologies on façade arises, as showed in Figure 90. This time the difference is lower, indeed almost 40% of the energy produced is self-consumed.

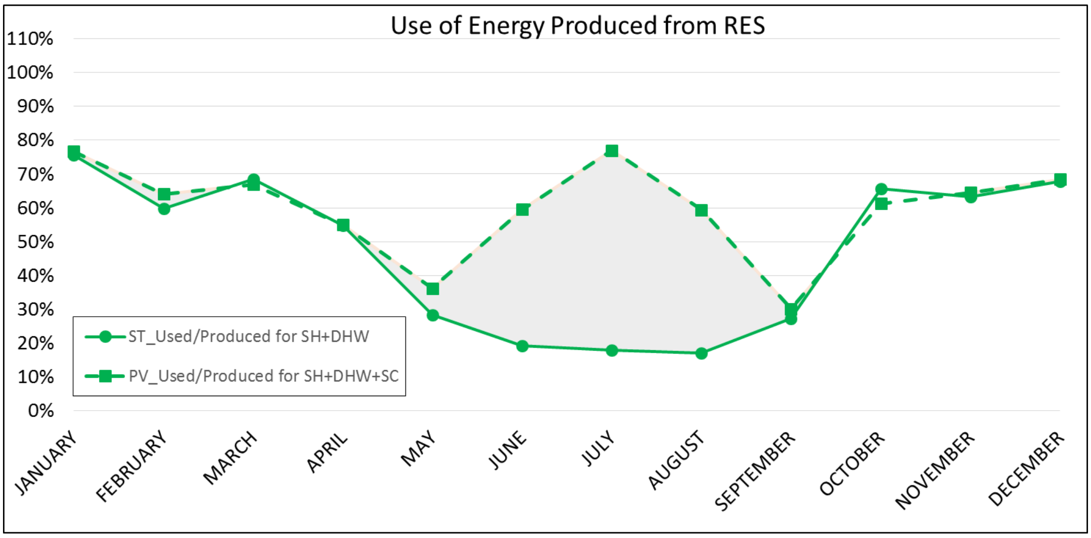


Figure 90 - STF Versus PVF_Energy self-consumption rate over the year (Stockholm)

As analyzed in the comparison between STF case and passive façade scenario, maintenance costs can have an impact on the cash flows over time such as to make more convenient the solution initially more expensive. However, costs depend on several parameters and factors. The cost for supplying natural gas and electricity is just one of these. Discount rate, presence and extent of incentives and financial support schemes, but also a rent re-evaluation in case of retrofitting or even for new constructions in comparison with the average built environment, can vary the attractiveness of an investment. It was noticed that the variation of the rent increase could significantly affect the trend of the costs of a solution. Coming back to the city of Bolzano, a first assessment of the two active façade scenarios was carried out without implementing any income. Annual energy cost increase rate was set at 1% and discount rate is 2%. Figure 91 highlights the different initial costs, whose gap widens over time despite the lower maintenance expenses for the solar thermal case. The higher energy savings achieved by the PVF scenario over the year affect significantly the comparison. A frequent maintenance was defined for both the scenarios; incidence of maintenance costs over the years is represented with the grey tones bars.

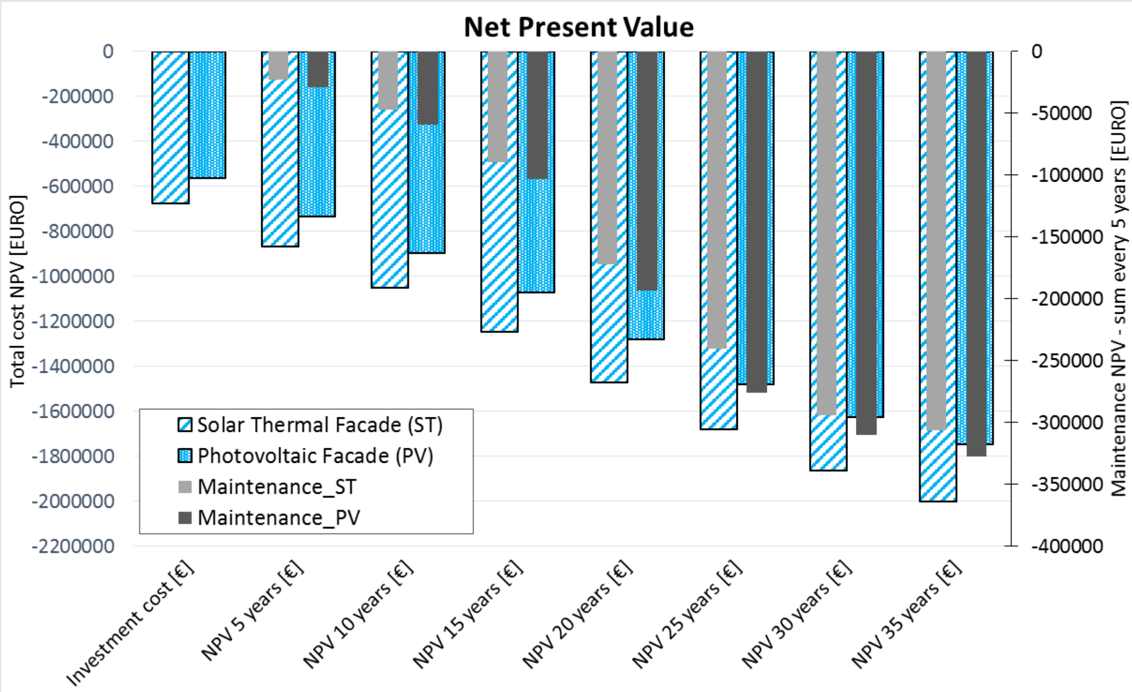


Figure 91 – STF Versus PVF_Net Present Value and maintenance cash flow every five years

Changing the perspective and introducing the variation of economic parameters, the PVF scenario can benefit from feed-in grid incentives in some countries like Italy.

Dashed lines reported in Figure 92 trace the NPV trend of the basic scenarios (STF: gray line; PVF: black line), hence with no incomes.

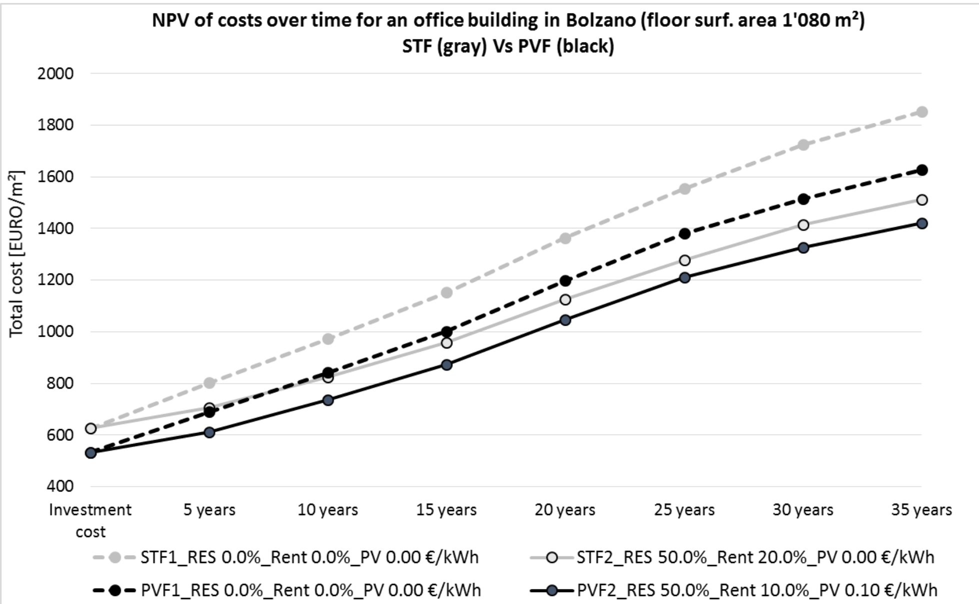


Figure 92 - STF Versus PVF_NPV trend depending on RES subsidy, Rent increase rate, Energy feed-in tariff

Another economic scenario for each design configuration was assumed. Concerning the STF case, a 50% grant for renewable energy based technologies and a 20% rent increase was considered, similarly to the previous comparison with the passive façade. The PVF configuration benefits from the same RES contribute, a 10% rent increase rate and a feed-in tariff of 0.10 €/kWh. The difference would remain pretty much the same over time as emphasized in the chart.

Considering the solar thermal façade configuration with no incomes as benchmark, the avoidable costs over time for both the active façade design solutions with economic parameters set as above are reported in Figure 93. Even though a higher rent increase rate has been applied for the STC case, the difference remains pretty much the same after 35 years.

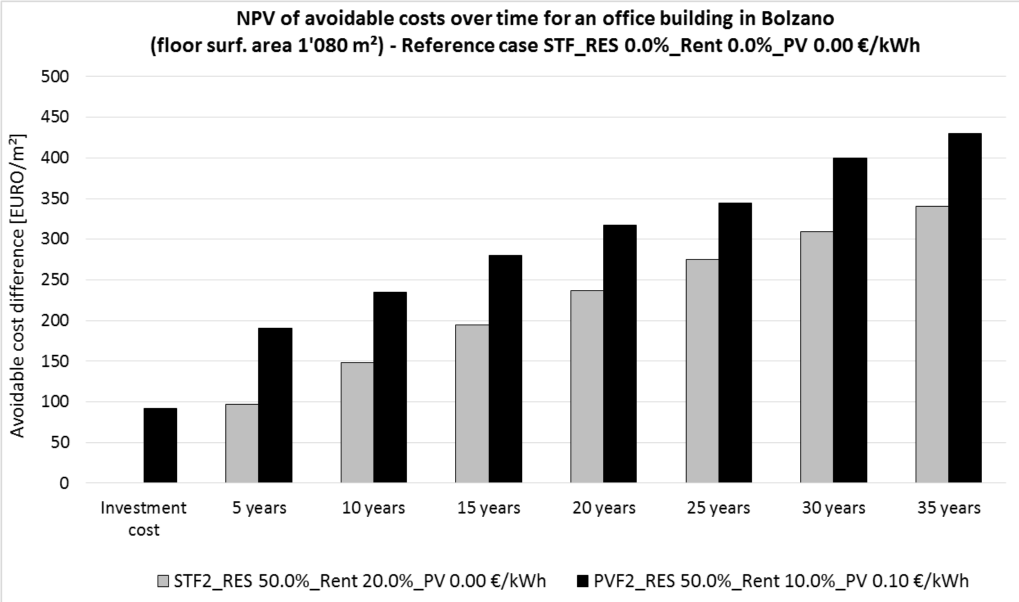


Figure 93 - STF Versus PVF_NPV difference depending on RES subsidy, rent increase rate (20% for STF and 10% for PVF) and PV feed-in tariff

It would be different if the STF design solution could benefit from a 30% rent fee increase. Indeed, the NPV would cross the PVF one after 15 years as showed in Figure 94.

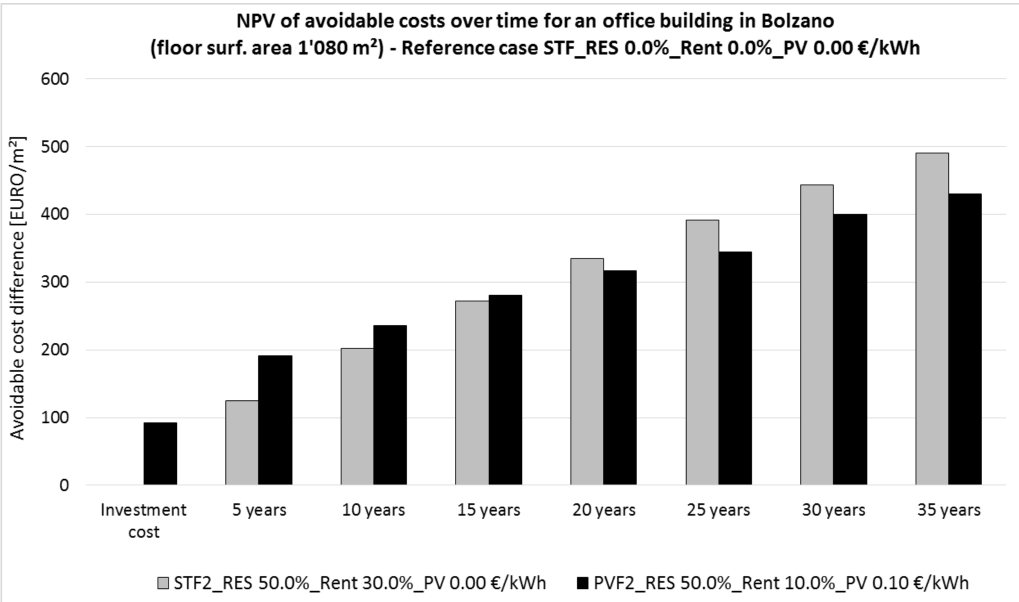


Figure 94 - STF Versus PVF_NPV difference depending on RES subsidy, rent increase rate (30% for STF and 10% for PVF) and PV feed-in tariff

Defining how much the rent for a building can be increased is matter for real estate companies. The author assumed that the BIST façade scenario could lead to a benefit due to the absence of fancoil units allowing to gain more space and the use of a wall radiant system avoiding the circulation of dust in the rooms, improving this way the air quality and work productivity. The photovoltaic façade solution can also take advantage of a higher monthly rent, for example due to a good design practice and technology integration between façade and energy system.

Other scenarios, involving solar technologies installed on roof for example, can be selected and compared within these terms. The next subparagraph is focused on the sensitivity analysis on several economic parameters, even if the tool limits the analysis to the variation of some preset parameters at a time.

5.2.3 Sensitivity analysis on economic parameters

Since this research work was advanced focusing on a solar thermal façade and a method to approach a business concept that can be built around it, it is important to understand at which extent an investment for an intervention involving similar concepts can be affected from the variations of economic parameters over time. This subject was partially introduced in the previous subparagraphs. A sensitivity analysis based on stochastic models would give better results, but it was not possible including this kind of analysis in FAST-IN. however, the tool can perform a rough estimation of the impact of different parameters. The limit lies on the variation of just a few parameters at a time. While it is difficult predicting failures of components over time, especially if the systems are new or barely explored, it can be easier assuming values to forecast the trend of some economic parameters that have an impact on an investment. The following analysis shows the impact of the energy cost (natural gas and electricity) and the discount rate, correlated one to each other and to the maintenance recurrence. These evaluations illustrate how hard can be the prediction of the net present value over the years, therefore the business of a technology. It has to be stressed that even though the tool grew out of a façade integrating solar thermal collectors, this analysis also aims to show the flexibility of the tool in comparing several technical solutions in terms of both façade concepts and energy systems.

One of the parameters already introduced in this chapter is the *rent increase* as a mean of building revaluation after a renovation process or simply a surplus value in comparison with existing buildings. Fixing a certain increase of the rent can play a key role in the cash flows trend over the years, leading in some cases to pay back completely the initial investment. Figure 95 displays the net present value of the building illustrated formerly, comparing the distributive façade (DF), hence unitized system integrating a radiant panel for heating and cooling, and a passive façade (PF) scenario with fancoil units as energy emission system. Both the solutions have a centralized boiler, a water storage and a chiller as energy generation and storage systems for heating and cooling. The higher cost of the first design choice is clear from the investment cost bars. Energy consumptions are the same. A regular maintenance recurrence was set for both the solutions, but relative bars show the higher upkeep cost for the PF case, due to the fancoil units. Since no energy production systems are integrated into façade or installed on the building, RES subsidies and feed-in tariffs are excluded. The only income item might be the rent fee paid by those who occupy the building.

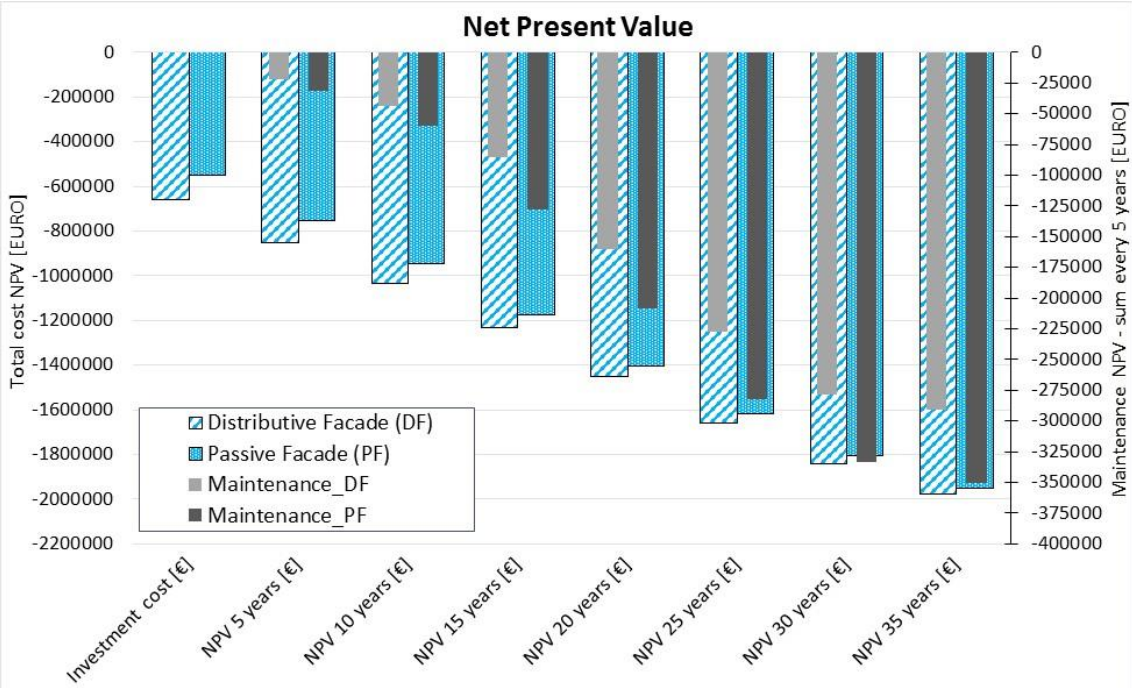


Figure 95 - DF Versus PF_Net Present Value for the two analyzed scenarios and maintenance cash flow every five years

If no extra incomes are implemented, the cost associated to the DF design solution remains higher over the years but the difference narrows from 100 €/m² (initial investment) to 50 €/m² (after 35 years) due to higher maintenance expenses for the PF case. If a rent increase rate is investigated, the former higher investment could become the more profitable. A potential higher rent fee for the DF case can be implemented, considering the aspects linked to the radiant panels system (more space inside office rooms, better indoor air quality). A 10% rent fee increase for the distributive façade case would lead to pay back the extra cost after 15 years if no markup is applied to the PF configuration. If the same rent fee increase is applied to the PF scenario, the DF configuration would be still less affordable, but cost difference would be lower than 30 €/m² after 35 years. In the end, a 20% increase of the monthly rent for the distributive case would pay back the extra initial investment after 12 years; delta cost for the two solutions after 35 years would be 120 €/m² in favor of the DF solution as displayed in Figure 96.

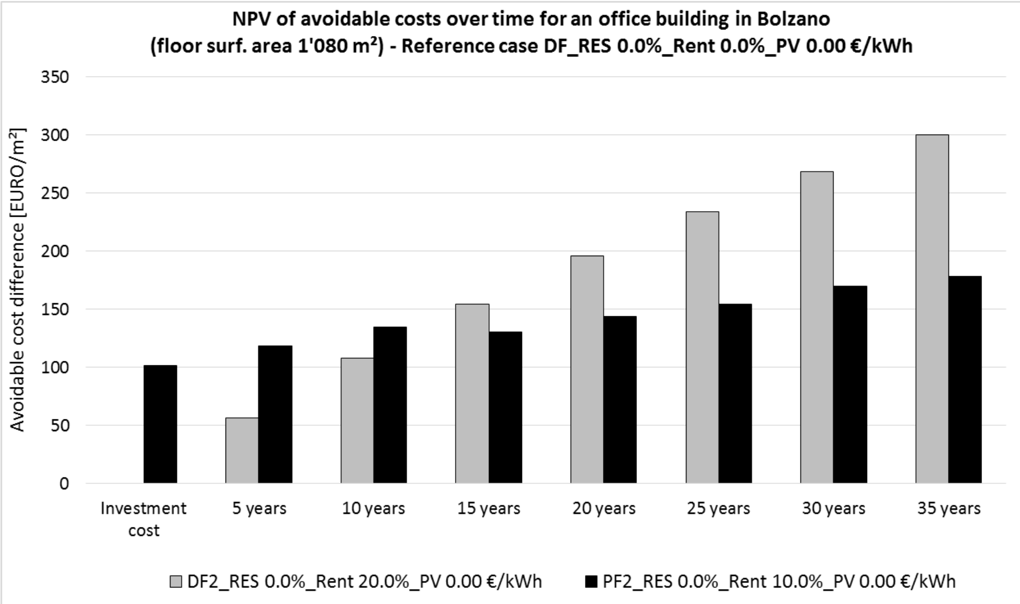


Figure 96 - DF Versus PF_NPV difference depending on rent increase rate

Another parameter the user can define is the possibility to accede to a *third party fund* for incentivizing innovative envelope solutions, therefore if the fund is non-repayable or is a loan (with an interest to be paid), the entity of this fund expressed as percentage of the investment cost and the years to get the money. To contextualize the study on this factor, the distributive façade (DF) concept is compared with the photovoltaic façade scenario (42 m² of PV surface area distributed on south and east façades). 70% of the produced electricity from the photovoltaic systems is assumed to be self-consumed to contribute covering several loads, while the rest is sent to the local grid. The second solution implements fancoil units as energy emission system. Both the technical scenarios have a centralized boiler, water storage and chiller as energy systems for heating and cooling. 50% incentive for renewable energy exploitation is implemented. The PVF related investment continues to be more profitable over time.

If a non-repayable third party fund is provided to the building owner to demonstrate a good practice for the DF case, the trend is different. It was hypothesized that 5% of total investment cost can be covered with this financing mechanism, within the first 5 years.

Figure 97 shows the NPV of the two design solutions with incomes implemented. It is evident the higher need of maintenance for the PVF case, including the substitution of the photovoltaic system. Thanks to the third party fund, the initial extra-cost corresponding to 126 €/m² of façade surface area can be paid back after 20 years.

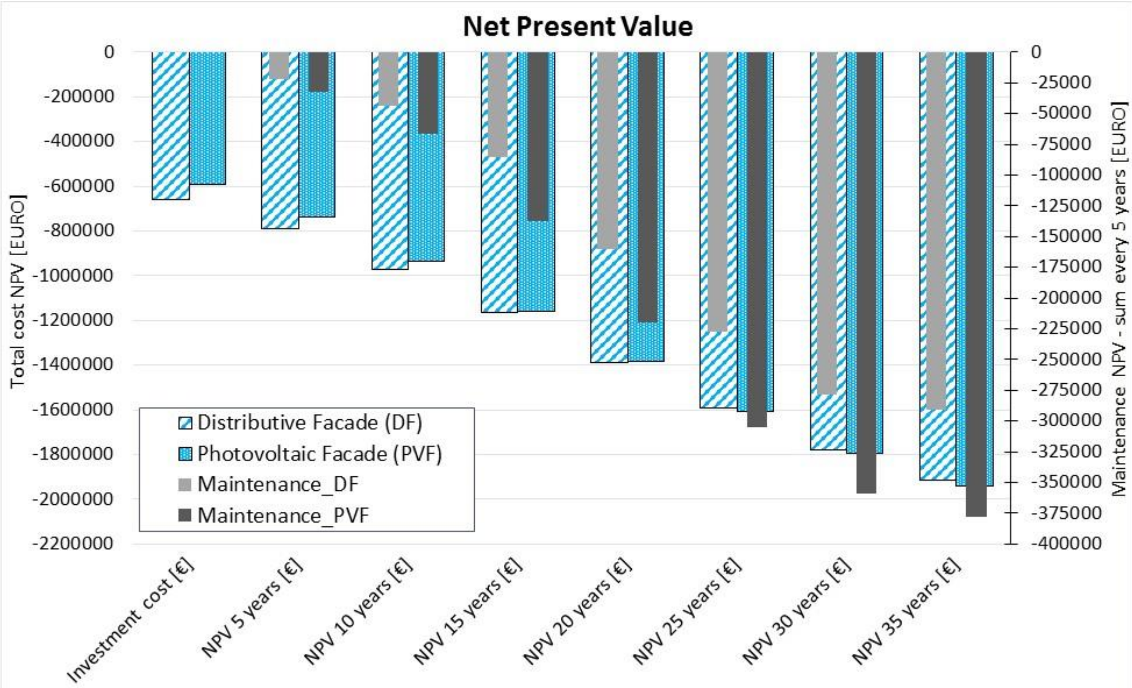


Figure 97 - DF Versus PVF_Net Present Value and maintenance cash flow every five years

Another discriminating factor the user can play with is the *energy cost variation* over time for both natural gas and electricity, which are the main energy sources. A limit of the tool is that only a linear variation can be implemented, therefore the same increase/decrease percentage is reported every year but calculated on the previous year cost.

Other comparative studies can be performed by means of the developed tool. These few examples showed the potential linked to the assessment of different façade and energy system solutions with the aim to not exclude design options without doing any performance-economic analysis involving a certain lifespan.

It was established that real costs of design configurations (envelope and energy system) do not just rely on the initial investment. Indeed the uncertainties linked to both technical and economic aspects can make more profitable a solution initially more expensive. The sensitivity analysis included within FAST-IN tool can be enhanced to consider more parameters at a time.

5.3 Potential improvements

FAST-IN tool is by far improvable. Inputs and feedback from façade stakeholders and skilled designers are necessary. It would be also interesting using as a case study a building with a façade built by a façade manufacturer to assess what would have happened if a solar thermal façade concept similar to the one used as case study had been applied. Benefits in terms of centralized heating system size are expected. Implementing the real size of energy systems and components has an effect on the Net Present Value over time. The first version of the tool just implemented simple rules of thumb to consider how many boilers or heat pumps would be necessary depending on the number of office rooms. A better energy model is necessary to refine results, especially when active systems are integrated into the envelope.

The interrelation between building energy needs and energy systems size is never immediate. It does not exist an instrument providing such an automatism. For this reason the user has not to completely rely on results emerging from the tool. This is valid for each software. These are preliminary calculations, which need to be detailed gradually with the definition of the final design.

The implementation of photovoltaic installations still requires improvements, starting from the thermal effect due to the integration into façade as assessed with solar thermal façades, but also from the configuration side. Indeed, now it is just possible defining the active surface to be installed on façade or on roof, without considering the pattern concept.

Analyses at office room level in terms of avoided and extra costs with reference to a standard room could be added to have a study more focused on the façade. Talking about the BIST façade concept, extra costs are linked to the operation of pumps inside the façade, while an avoided cost is the non-installation of fancoil units if a radiant panel is integrated as for the façade case study.

The graphic interface can be upgraded. Excel is quite comfortable to be used and almost everyone know it. The limit lies on the capacity to manage many data and charts, and on creating links among different sheets. These are items bringing to heavy spreadsheets. It is expected the use of specific software to write a code helping to manage data.

Future developments of the tool for a more widespread implementation should be aimed to:

- *Allow the user to create a more detailed geometry to model real life buildings (possibility to have more than four façade orientations, more detailed room geometry input, ...)*
- *Integrate the external shading from close buildings and horizon*
- *Cover more than just the office building typology (housing or façade renovation projects)*
- *Increase the user-friendliness depending on the expected target groups*
- *A comparison of the tool with other reference schemes like solid or wooden construction systems with different heat insulation system*

Chapter 6

6 Conclusions

Finding business models based on the potential of active façades is an extremely modern topic of research. The potential is linked to the façade as energy deliver system, where the centralized system turns as back-up element. Nevertheless, the business concept should be also connected to need of retrofit strategies through the use of new façade technologies needing a boost to access the current market. The scarce success of innovative façade solutions is partly due to the difficulty to communicate the integrated energy concept among façade stakeholders. That is why this research project has been finalized with a user-friendly tool thought to bridge the gap in communication between designers and façade manufacturers and investors. Technology, performance and economic related aspects are implemented to give a first impression of the meaning of integration of active technologies into façade. This chapter highlights the most important findings of the research and suggests areas for further investigation.

6.1 Main results and outcome of this work

This research project was aimed to find a means to support business concepts for solar thermal façades, helping to understand the potential linked to a façade-integrated energy system. It ended with an excel tool that can help designers and façade manufacturers to assess the potential of active façade concepts and evaluating critical points and uncertainties. Therefore, the object was expanded to solar façades or façade systems that can take advantage of a connection with energy systems.

The work started from a specific façade concept developed within an industrial research project pursued by *Stahlbau Pichler* in parternship with *EURAC Research*. The façade system is a unitized curtain wall conceived to produce, store and distribute energy. This multifunctional envelope system allows the production of thermal energy to cover the space heating and domestic hot water demands in office buildings; if that is not the case, the façade system is activated to remove the produced heat, avoiding or minimizing the risk of stagnation. Finally, the radiant system integrated into façade can work as heater and cooler through the connection to the centralized energy system. Working in close collaboration with a façade manufacturer was helpful to discover and carry on the technology part, from the first sketches to the prototype construction. The preparation to the test phase gave insights about the complexity of the hydraulics integrated into façade in terms of components and the number of controls necessary to make sure the system could work as desired.

Economics and technology-performance aspects were carried on in parallel to have a comprehensive vision of the façade case study, from which originated the idea to expand the analysis on active solar façade systems.

The lack of communication among façade decision makers as research question

The research question led to an analysis of the façade design process to understand risks and implications determining the high investment costs characterizing the advanced façade solutions. One of the main barriers for active façades is the lack of communication between designers, façade manufacturers and investors. Each one of these figures has specific resources and skills, which are necessary to design, produce and install active envelope systems, but an instrument helping to bridge the gap in communication is still missing. This instrument has to be easy-to-use. Furthermore, it has to provide significant results in a reasonable time since design and construction process schedules are very pressing.

The main result of this research has been a tool aimed to be used by building decision stakeholders with a specific regard to the building envelope and the energy system. Since the decisions made during the early design process are the most effective, the instrument is thought to be used during that timeframe. The designer can define the façade concept, configure the building façade and decide which technologies have to be implemented, including the building energy system. The façade manufacturers can contribute by defining the façade related costs from the production stage to the installation and during the whole envelope lifespan. Together, they can assess the necessary investment cost and the influence of operation and maintenance outgoings during the building lifetime or a specific period. Since item prices, maintenance recurrence, energy systems efficiencies and financial policies vary region by region, the users can define pretty much all of these parameters to better contextualize the study. This first version of the tool allows to compare two building scenarios at a time.

As stated in the dissertation, a business concept is based on assumptions. The presented tool allows the user to do assumptions and verify the weight of the choices on the economics, which are the driven aspects of every investment.

During the research work, it clearly emerged the need of energy simulations to assess the performances of active façades. The modelling detail is a matter of building physics knowledge and availability of dedicated software. Indeed, one could just rely on simplified estimation of the solar energy potential and extract some information for better positioning active technologies on façade. However, this approach would not allow to know what is happening into the façade from the thermal point of view. Quantifying favourable or adverse heat fluxes through the façade construction is crucial. For this reason, façade thermal analyses are recommended to investigate the range of temperature variation, which might be crucial for the choice of materials. The research focused the attention on mono and bi-dimensional studies, which were considered suited for the mentioned purposes. A 3D model could be useful to investigate thermal bridges and the effective façade heat losses, but it would also require knowledge for modelling and time for computing. Finally, energy dynamic simulations for built environments are needed to assess the influence of façade systems on the energy consumptions and indoor comfort.

From the design and construction process of the solar thermal façade case study, several technology questions arose. Hydraulic connections are by far the most relevant issue to be faced in a solar thermal façade. One fundamental aspect is ensuring the maintainability of the system from the inside of the building without demounting the entire façade module. Connections between façade modules were not tested, but guaranteeing an easy junction of modules is a key element to succeed with this façade system. Ergonomics for installation of active façade modules is a topic to be tackled. As for the solar thermal systems installed on roof, the problems during the summer season have to be challenged. Depending on the amount of solar thermal collectors to be installed on façade, it may change the liquid circulation modality. Indeed, for a low-rise building a drain-back system might be installed to empty the collectors during summer, avoiding this way the heat transfer through the façade. This system would not be suitable in case of mid-rise buildings since a huge storage tank would be necessary and pumps would push the water to relatively high levels. The other solution is a continuous circulation of water during sunny days to remove the heat from the façade. Regardless the liquid circulation modality, a centralized storage system is necessary for both the cases.

Façade systems integrating technologies taking advantage of renewable energy sources produce clean energy and can provide a good aesthetic image if the installation takes into account both performance and architectural criteria. Still, these considerations are not enough to make similar systems a technology promise to be inserted into the market. As long as these solutions are not appropriately supported by financial polices and contributes like third party funds with no loan, it is arguable their market penetration. Due to the high design quality and the dislocation of services into façade, the building should acquire a higher economic value in comparison with standard façade and energy system solutions. For this reason, the extra-cost due to the integration of active systems should be incentivized, provided that integration criteria are respected and performance are assessed.

The implementation in the FAST-IN tool of technology-related aspects, but also energy performance-related features give to the obtainable results the right significance of construction works assessment, not only based on the initial investment. The possibility to set a maintenance plan during the building lifetime and the analysis of the cash flows showed that high-priced scenarios at construction time, actually could lead to a more profitable investment within the short period (5-10 years), depending on the economic boundary conditions. Differently from Life Cycle Cost Analysis tools, where costs are required as lump sum, FAST-IN tool allows the user to comb through the costs related to both the initial investment and the operation and maintenance. This way the investor can be aware of the extent of the various items (building site arrangement, envelope systems, energy generation systems, energy distribution systems and others) on the initial cost and the incidence of operational expenses on the net present value over time.

The difficulty to find and communicate requirements, performances and costs of complex (but also standard) facade systems has been the springboard of the research exposed with this dissertation. Building owners might be in favor of innovative envelope solutions, giving to the construction an iconic image or an added value, but they want to be sure the complexity of the façade and the possible integrated energy concept is not going to increase the investment costs without achieving any benefit. When it comes to complex, but also ordinary, façade systems it is not always clear which are the involved costs besides the initial investment. We are used to thinking about some features as performance indicators, for example the thermal transmittance of the envelope, but actually these parameters are not giving the building user/owner a feedback on the energy use, the achievable comfort or the costs to maintain the building. The effect of design choices and uncertainties should be quantified in financial terms over time; since this evaluation should start from the early design stage, a user-friendly tool addressed to technical managers, engineers and architects interested was developed. The excel spreadsheet, called FAST-IN tool, is aimed to support the user to set priorities, while evaluating several envelope-energy system configurations through a technical and economical assessment of selected interventions. The strength of the instrument is linked to the multidisciplinary-based approach giving the user the chance to set inputs relative to technologies, maintenance recurrence and related costs, energy efficiency and financial mechanisms to bear the initial cost and eventually pay back the extra-cost of investment in comparison with other solutions. The outcome of the tool is not providing technical details of façade and energy systems, indeed this output comes out from the experience of designers and façade manufacturers. Rather, the instruments allows to rapidly assess the weight of some technical choices and economic reservations (materials and components' costs, presence of subsidies, building value increase, energy tariffs, third-party funds), which all influence the net present value trend. The powerfulness of the instrument is based on getting performance figures in form of charts showing energy use distribution over the year, their coverage by means of RES-based technologies and thermal/visual comfort. On the other hand, economic indicators, which more interest decision makers, are showed in terms of net present value (NPV) trend to quickly judge if a specific investment could be worth under specific assumptions that are necessary to analyze a business concept. The charts help to understand what happens within a specific timeframe in terms of cash flows after the investment: the tool's user might want to see if the investment is paid back within a reasonable time linked to warranties of components or specific needs within the building investor's business plan; FAST-IN tool allows to do this in a fast way.

6.2 Future developments

The tool was initially focused on the façade case study that is a solar thermal façade for office buildings, but the proposed methodology must not be limited to this solution. Indeed, façades are expected to become more and more important from the energy point view. Concerning the passive side of façade systems, improvements recently have headed to consolidated façade technologies, but regarding the integration of active functionalities, a big potential has still to be discovered. By talking about façade integrated-services with designers and façade builders, the scepticism of someone comes out. There again, others are really convinced in thinking to façades as decentralized energy delivering systems. The envelope is not removing the building energy plant, but it is moving components to the peripheral part with the hope to reduce the size of the centralized system and gaining useful living/working space. Building research and design are following the tendency to get personalized and flexible building services. The building elements suppliers are expected to provide new service packages to answer the users' needs in terms of better performance, comfort in use and costs over time. The tool is going to be improved through the addition of other façade integrated-service solutions like decentralized mechanical ventilation units with heat recovery. Since the PV installation on façade was marginally approached in comparison with solar thermal systems, a better implementation considering the involved building physics is expected. The *Technology Implementation* sheet is the starting point to have a tender specifications' document structure; other items falling outside the envelope and the energy systems will be included to have a comprehensive technology-performance-economic analysis.

With regard to energy modelling and simulation, some improvements are still necessary. More specifically a 3D FEM analysis would help to understand the whole façade performance, including also the transparent part. The model can be validated with data obtained from the experimental campaign carried out at the *EURAC* laboratories. The design of the active portion could be further improved in terms of insulation material and thicknesses around the water storage. Dynamic energy simulations at building level are necessary to study potential strategies of heat generation exploitation; for example, thinking to create a low temperature district heating at neighbour scale, the water loop could be used as heat sink for the extra thermal energy production from façade. This way, a feed-in tariff could be applied and the cash flow analysis would become more favourable.

The FAST-IN tool still needs a functional validation, which is going to occur thanks to new collaborations and applications on building case studies included in commissioned projects coordinated by *EURAC's Institute for Renewable Energy*. The database of costs for supplying materials and components, maintenance costs and recurrence, productivity to perform specific construction works determining the installation time are continuously added and updated. The tool should allow to evaluate both new constructions and retrofit scenarios. Based on the interviews carried out with façade manufacturers, the tool can find application during the early stage of the design process of buildings to assess the economic impact of choices related to the façade and the energy system. Hence, the research can be applied to the design development. It would be interesting using a building built by *Stahlbau Pichler* as case study for the tool to assess what would have happened if an active façade concept and the proposed method had been applied. Regarding the consistency of the numbers used in the tool, some have been assumed but several values concerning materials, components, energy systems have been discussed with experts (both researchers and companies) to find possible ranges. Applications within research projects are necessary to create a database of costs, maintenance recurrence, components' lifespan and all of the values the user can freely insert. Better if a country can be selected and costs related to that nation are displayed. On the other hand, the user can freely insert values coming from her/his ordinary practice. The tool is not an advanced instrument but it finds its originality in the multidisciplinary analysis. The most appropriate figure called to use FAST-IN tool is the designer, who makes feasible the desires and decisions of the client/owner of the building. Façade and energy consultants can be invoked to give reliable data (costs, maintenance requirements) on subjects concerning their sphere of action.

Even though it was only approached, the prototyping stage was fruitful and gave some hints for future improvements of the product. Indeed, this is a prototype developed to demonstrate only the façade thermal performance and the definition of control strategies to activate the different functionalities. Enhancements concerning both the architectural and functional integration are possible. However, choosing the dynamics to be investigated in a solar thermal façade is not an easy task. Once the tests will be finished, a sort of guideline to approach the test of solar thermal façades is conceivable.

Finally, a business strategy for a façade system should include all the steps to demonstrate the feasibility of the technology, especially the fulfilment of the standard requirements like fire codes and generally the safety in use, which would include impact resistance of solar thermal collectors and every technology used as external façade layer. The real durability and the sustainable use of resources should be quantified.

The method developed in the thesis could be enlarged for a more widespread practical application of solar thermal facades, adding information needed for overall business models and more fields of practical application (Customer, market offer, revenue and financial models, more variants for technical applications on different building typologies, geometries, and operational processes and policies). According to Karl Höfler from *AEE INTEC*, FAST-IN tool could support the market uptake of active façades, but an effort for widening the spectrum of assessable scenarios and for enhancing the friendliness of the instrument is necessary.

A research team within the *Delft University of Technology* is developing a circular business model based on the use of façades as performance delivering tools [107] within a project called *Façade Leasing*. Under this scheme, the client is no longer the owner of a number of building components, but instead leases them from the manufacturer using long-term service contracts. The work illustrated in this dissertation could proceed through a collaboration within the COST Action 1403 (Short Term Scientific Mission) at the TU Delft Façade Research Group.

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