CRANFIELD UNIVERSITY

IÑIGO MARTIN COTO

Review of the Different Building-Integrated Solar Technologies

School of Water, Energy and Environment (SWEE)
Renewable Energy

MSc
Academic Year: 2020 - 2021

Supervisors: Dr Heather Almond, Dr Peter King

CRANFIELD UNIVERSITY

School of Water, Energy and Environment (SWEE)
Renewable Energy

MSc

Academic Year: 2020 - 2021

IÑIGO MARTIN COTO

Review of the Different Building-Integrated Solar Technologies

Supervisor: Dr Heather Almond, Dr Peter King

This thesis is submitted in partial fulfilment of the requirements for the degree of Renewable Energy
(NB. This section can be removed if the award of the degree is based solely on examination of the thesis)

ABSTRACT

The transformation of urban areas into more self-sufficient and carbon-free places is indispensable in the fight against climate change. 36% of global energy consumption comes from buildings, mainly in cities. If all available and suitable surfaces of these buildings were covered with solar devices, up to 22% of the electricity demand could be supplied, according to an EU study. One of the most advanced and aesthetically pleasing techniques is that of building-integrated technologies, whether they are photovoltaic modules producing electricity or solar thermal collectors producing heat. The main objective of this thesis is to carry out an extended literature review of all existing building-integrated technologies and the methods used to integrate them. In addition, a small compilation of the most relevant projects completed to date will be presented, and proposals will be made for Cranfield University to move closer to zero-emission energy consumption.

Keywords:

Aesthetics, architectural integration, concentrating, efficiency, energy output/yield, hybrid, integrability, photovoltaic, solar irradiance, solar thermal.

ACKNOWLEDGEMENTS

I would like to thank everyone who has supported me during the research and writing process of this project. First I would like to thank my two supervisors, Dr Heather Almond and Dr Peter King, for their enormous and invaluable assistance throughout the thesis project. I would also like to thank the many other professionals on campus who have assisted me during this period by answering numerous questions and providing me with access to certain information. Finally, I would like to express my gratitude for the unconditional support of my family, especially my parents, and my friends, without which nothing would have been possible.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

3D	Three dimensions
a-Si	Amorphous silicon
AC	Alternating current
AM	Air Mass
BA	Building-Attached
BI	Building-Integrated/Building Integration
BICPV	Building-Integrated Concentrating Photovoltaic
BICS	Building-Integrated Concentrating Solar
BICST	Building-Integrated Concentrating Solar Thermal
BIPV	Building-Integrated Photovoltaic
BIPVT	Building-Integrated Photovoltaic/Thermal
BIST	Building-Integrated Solar Thermal
C	Concentration ratio
c-Si	Crystalline silicon
CdSe	Cadmium selenide
CdTe	Cadmium telluride
CFC	Chlorofluorocarbons
CI(G)S	Copper indium (gallium) selenide
CO_2	Carbon dioxide
CPC	Compound Parabolic Collector
CPV	Concentrating Photovoltaic
CSP	Concentrating Solar Power
CST	Concentrating Solar Thermal
CZTS	Copper zinc tin sulfide
DC	Direct current
DHW	Domestic Hot Water
EPW	Energy Performance Contract
etc.	etcetera
EU	European Union
GPP	Green Public Procurement
GW	Gigawatt
HCFC	Hydrochlorofluorocarbons
km	kilometre
LCoE	Levelized Cost of Energy
LSC	Luminescent Solar Collector
m^2	Square metre
µm	micrometre
MIT	Massachusetts Institute of Technology
MW	Megawatt
N	North

p	pence
PCM	Phase Changing Material
PPA	Power Purchase Agreement
PV	Photovoltaic
S	South
ST	Solar Thermal
TWh	Terawatt-hour
USA	United States of America

1 Introduction

In the fight against climate change, the structural transformation of the current energy system is essential. This message seems to be getting through to more and more countries, as can be deduced from programmes such as the Paris Agreement or Horizon Europe, among others.

Due to the rapid urbanisation of many countries, a large part of the world's population lives in cities. As a result, more than two-thirds of global energy consumption originates in cities, of which approximately 36% is accounted for by total consumption in buildings. This value is considerably higher in Europe, accounting for 49% of total consumption and 36% of total $C0_2$ emissions (Guillén et al., 2019).

For this reason, more and more emphasis is being placed on sustainable buildings that reduce their carbon footprint through various techniques. Lately, one of the possibilities attracting the most attention is building-integrated solar energy, especially photovoltaic but also thermal.

According to a study on the solar potential of buildings in the EU-27 (Defaix et al., 2012), if it were to be fully covered by 2030, it could provide up to 22% of the total electricity demand in these countries. In other words, 951 installed GW for an annual production of 840 TWh. As shown in Figure 1, roofs have by far the most considerable potential, although south-facing facades would also have a large niche, especially in taller buildings.

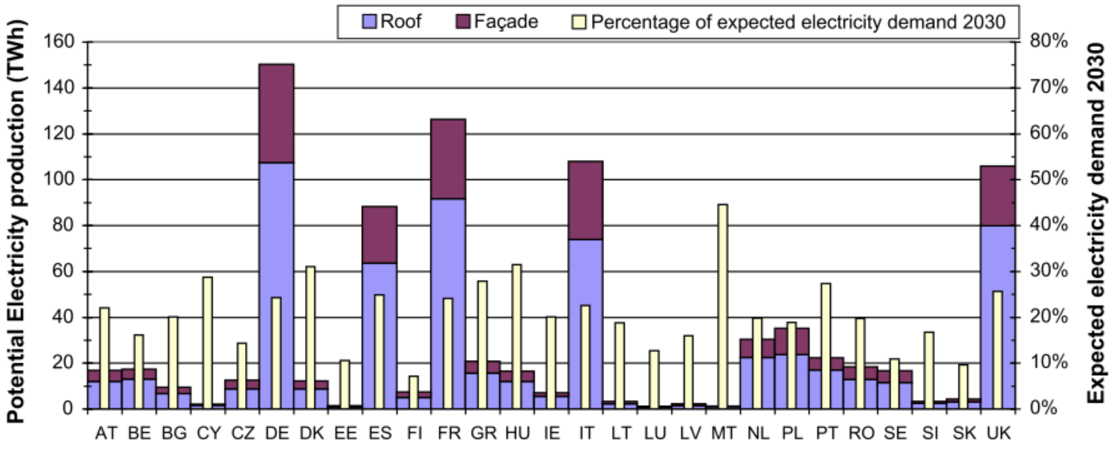


Figure 1. Potential of Building-Integrated Solar Energy in the EU-27 (Defaix et al., 2012).

One of the reasons that makes this integration technique so attractive is precisely the energy-producing technology it uses. Solar PV is one of the most widely deployed technologies, and presumably, it has one of the best futures. This can be explained mainly due to the immense existing solar potential in many regions of the planet and to the massive drop in LCoE over the last decade (IRENA, 2020), the largest among the leading renewable technologies, as can be seen in Figure 2.

Another technology that also harnesses solar irradiance to generate thermal energy and has also been considered for building integration is ST. It is not as competitively priced as PV but has come down enough to compete with fossil fuels. However, it is not yet being deployed on a large scale despite its enormous potential in some regions.

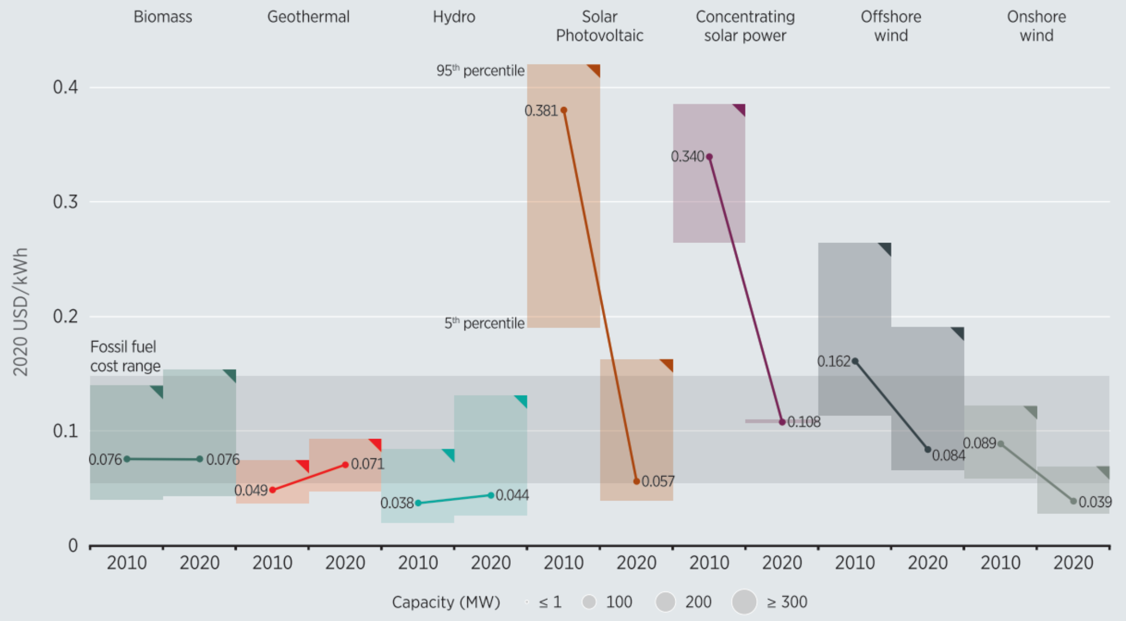


Figure 2. Comparison of global LCOEs of the main renewable technologies between 2010 and 2020 (IRENA, 2020)

While it is true that solar potential varies widely depending on geographical location, it is a resource found everywhere. Countries with the highest potential tend to be generally warm and dry climates and low seasonality. These are usually in the mid-latitudes, close to the tropics.

However, countries like Japan or Germany are in the top 5 of the largest producers (IEA, 2020) despite their generally warm/cold and not very sunny climate. This shows that even if the climatic conditions are not very favourable, the solar potential is large enough in most countries to use solar technologies. Another clear example is the United Kingdom: if all the territories between the 60º N and 60º S parallels (where data is available) are taken into account, this country as a whole has the second-lowest PV potential in the world, only behind Ireland (ESMAP, 2020). However, it is the world's eleventh most important producer of photovoltaic energy (IRENA, 2021), supplying 4% of the country's demand in 2019 (IEA, 2020).

1.1 Objectives

This report aims to gather all the existing Building-Integrated Solar Technologies (either in the design or implementation phase) to provide an overview and be a possible starting point for future university projects and research.

Other more specific objectives are:

- To provide an overview of each of the existing building-integrated solar technologies to promote a better understanding of their general characteristics and requirements.
- To raise awareness of the advantages offered by these technologies concerning the use of urban space and energy potential, the transformation of the energy production system and the cost savings.
- To address the importance of the architectural integration of these devices in buildings and how mismanagement of this issue can lead to significant social rejection.
- To apply all the gathered knowledge in a simple case study.
- To give a short and medium-term vision of the possible advances and development in this specific field of solar energy harvesting.

1.2 Methodology

The structure of this report is based on an extended literature review. To begin with, an exhaustive search of all available studies and articles on this topic will be carried out. Once as many relevant articles as possible have been gathered, these will be classified according to the topics covered. Then, the general structure of the project will be devised to proceed with the writing of the project. The next step will be to put into practice what has been learnt in a practical case study, followed by the section dedicated to the conclusion and final discussion.

As additional information, a Gantt chart will be used to establish deadlines for each section of the project.

2 Building Integration of Solar Technologies

Building integration of solar technologies, as the name suggests, consists of incorporating either PV panels or thermal collectors into the building. Something not to be confused with, and probably more familiar, is attaching them to the structure, known as Building-Attached or simply BA. In the latter case, the devices are fixed to the surface, whereas in building integration, they replace a part of the surface into which they are being embedded, although there are some exceptions. This means that in addition to their primary function as energy producers, these elements also have to fulfil at least some of the functions of the part of the building they are replacing.

2.1 Early history and current situation

The first prototypes were built in the USA in the late 1930s. It all started with the MIT Solar House I, the world’s first active solar house (see Figure 3). It was built in 1939 in Cambridge, Massachusetts, and the solar installation consisted of flat-plate collectors along its sloping roof (Levy, 2017).

Figure 3. MIT Solar House I, first-ever BI solar prototype (MIT Solar Decathlon Team, n.d.).

In those early years, the prototypes carried out only had ST devices, as conventional PVs did not appear until the 1950s and were not commercialised until the 1970s (Kuchta, 2021), while the former began to be developed centuries earlier (Szabó, 2017). It was not until the 1970s that developers started to realise that working with architects on the aesthetics of projects would be necessary if BI was to have a future (Becker et al., 2017).

In the 1980s, despite several decades having passed, active solar energy still received little attention in the design of green and self-sufficient buildings. That attention was still mainly focused on passive solar architecture, intending to optimise the sun’s light and heat through south-facing windows (in the northern hemisphere) and good insulation. Active solar energy was considered in the designs, but conceptually only due to its uncompetitive prices (Herzog, 1996).

It was not until the 1990s and early 21st century that the designs presented and built became more natural and plausible. In addition, due to the enormous drop in price, PV options started to become more important than ST, even though the latter was already considered a fully mature energy source.

It was also in these years that several prizes started to be awarded: the Swiss Solar Price in 1990 (Becker et al., 2017), the European Solar Prize in 1994 (EUROSOLAR, n.d.), the SeV Architecture Prize in 2000 (Bavarian Association for the Promotion of Solar Energy, 2020) and the Solar Decathlon in 2002 in the USA (US Department of Energy, n.d.) and 2007 in Europe (Vega Sánchez, 2011), among others. Although most of them were not held annually initially, this helped to promote research and project development in this field, and many innovative ideas and designs were created.

This and the recently approved incentives are probably why mainly European countries and the USA are the world leaders in this sector. In 2015 they accounted for almost 65% of the world’s installed BIPV capacity, which in that year was 2.3 GW (Osseweijer et al., 2018). This accounted for approximately 1% of the global PV market.

Although there is no official data, forecasts said that by 2021 the installed capacity would have risen to 13 GW worldwide (Onyx Solar et al., 2016). Thus, many countries intend to increase the share of BIPV within the PV sector, such as the Netherlands, which set a target of reaching a 5% share by 2020 (van den Hurk and Teunissen, 2015).

2.2 Benefits

Two main benefits differentiate this technique from BA:

- Savings in building components. This is mainly the case in new buildings that are already built with integrated devices. In these cases, builders are spared the elements that the panels or collectors replace instead of when these devices are attached. This saving also occurs when, for example, a surface is due for refurbishment or replacement, and instead of replacing it with a standard new version, a BI device is installed.
- The enhancement of the aesthetics of the building. In contrast to what is usually the case with attached devices, when using BI, buildings that have suffered more from the passage of time or that were not designed with their appearance in mind can achieve a very positive change of image.

In addition to these, there are other benefits that buildings with BA facilities also share, among others:

- The saving of non-urban land that would be necessary to install the same solar power. This is particularly attractive in cities: on the one hand because the available land is quite limited due to their high population density; on the other hand, because it is 0 km energy, and therefore heat losses in transport are avoided.
- The savings on electricity bills for consumers. All energy produced by the devices does not have to be purchased from the grid, and if there is any surplus, it can be sold to the grid or stored in batteries.
- The reduction of the carbon footprint of homes, businesses, institutions, etc. Although the extraction and construction of the elements that make up the solar collectors and panels do have an environmental impact, the energy production phase is entirely emission-free.

2.3 Functional and constructive requirements for BI

In BI, an essential aspect to consider is the functionality of the devices when it comes to protecting the interior of the building. Although it is true that depending on the surface, or even the type of building in which they are integrated, the situation varies, there are certain general aspects to be taken into account (Munari Probst and Roecker, 2011):

- It has to offer protection against rain, wind and noise
- It has to insulate the interior from both winter cold and summer heat
- It has to regulate light transit in some cases properly. This is especially important when solar devices replace windows or facades/roofs that allow some or all of the sunlight to pass through
- It also has to allow the flow of fresh air, when this is deemed necessary

In general, they have to ensure that indoor conditions are optimal, both for the occupants and for all material goods. The requirements in this respect vary greatly, depending on the type of building and its purpose, the geographic and climatic characteristics of the site, etc.

The constructive aspect is something to be considered as well. In other words, it must be ensured that the panels or collectors installed meet the construction requirements of the chosen surface (Munari Probst and Roecker, 2011):

- The load of the device must be adequately transferred to the main structure using a suitable attachment
- Its integration should prevent the surface heat transfer from varying negatively, as well as thermal bridges from being created
- It must be able to withstand fire and weathering
- It has to be able to withstand possible wind loads and impacts; and, in case of damage, not pose a risk

2.4 Architectural Integration

When integrating a PV panel or a ST collector, it is becoming increasingly common to have a more global and symbiotic view of the different aspects that affect this process. In other words, in addition to taking into account the functional and constructive aspects of the installation, everything related to its aesthetics and the impact it causes is also considered.

Architectural integration is therefore said to be achieved when the solar installation blends in as well as possible with the rest of the building and its surroundings. Furthermore, it seeks to reinforce and enhance the aesthetics of the building by adding value to it. An important aspect is also to achieve social acceptance, which is essential in any high-quality project.

This method can be very beneficial in existing buildings. Aesthetically speaking, refurbishing and enhancing existing buildings is necessary in the search for more pleasing urban environments. However, in these cases, the integration work is often more arduous and costly, as the standardised products available are often not suitable. For this reason, custom-made and innovative products are often required.

In new construction projects, it is easier to achieve a good architectural integration without the cost being too high. As it is an integral part from the very first design phase, the structure is adapted to the requirements.

A drawback of pursuing this objective is that the energy yield of the installation is often compromised. There are several factors to take into account when it comes to good architectural integration. In many cases, when trying to make the appearance more pleasing by manipulating colour, shape or texture, among others, the energy performance is affected. A comparative assessment of these factors for both PV and ST has been carried out in Chapter 4.

3 State of the Art

3.1 Building-Integrated PV

PV is currently the most common of all building-integrated solar technologies. While it is true that solar thermal has been considered a mature technology even before PV, the enormous development and consequent drop in the price of the latter has made it by far the most commercialised and developed.

Within the BIPV technology, there are two types: grid-connected and stand-alone. Most commonly, especially in countries with a good electricity infrastructure, the installation is connected to the grid. In this way, surplus production can be sold through the grid; and in case of insufficient production, it is possible to buy it from the grid. The stand-alone option tends to be more common in developing countries. In these cases, the use of batteries is indispensable in the absence of other energy sources.

3.1.1 Basics of PV

PV cells produce electricity thanks to the photovoltaic effect. Roughly explained, when photons hit the cell, a voltage difference is created, which induces an electric current. This voltage difference occurs between the two semiconductor plates that mainly make up the cell.

Semiconductor plates are usually composed of the same material, but impurity atoms are added to charge them. Thus, p-type semiconductors have holes or positive charges added to them, while n-type semiconductors have electrons or negative charges. These are joined together to create what is known as a p-n junction. Finally, when photons of a specific wavelength strike the semiconductors, the charges move towards the opposite plate, making a voltage difference. When connected to an external circuit, this creates an electric current (Simya et al., 2018).

The electricity produced by these devices is DC. Considering that both for the connection to the grid and to the home itself it is necessary for it to be AC, the use of an inverter is indispensable.

3.1.2 Technologies used in BIPV

The use and development of BIPV technologies runs entirely parallel to that of conventional PV cells. However, there are still some difference

Although many PV options are available today, the ones produced on a large scale can be grouped into two families: first and second-generation cells.

First-generation solar cells

They were the first cells to emerge and still are the most popular ones in both the PV market, with almost 95% of the market share (Fraunhofer Institute for Solar Energy Systems, 2021), and in the BIPV market, with just over 73% (Arizton Advisory & Intelligence, 2021). That difference is probably due to the advantages that certain features of some of the lesser-used PV technologies bring to BI applications.

They are also known as crystalline silicon, as they are made from blocks or ingots of silicon. There are two types of c-Si cells: monocrystalline ones, when the ingot is made from a single continuous crystal; and polycrystalline ones, when a mixture of different crystals is used. This is why monocrystalline cells have a homogeneous appearance, while polycrystalline cells have multiple shades (see Figure 4).

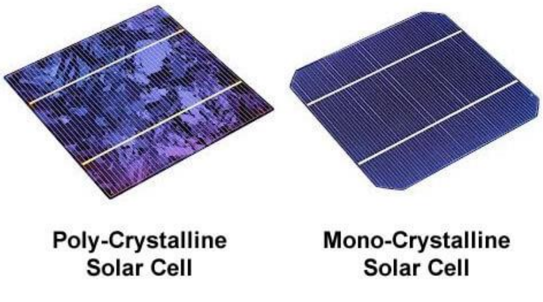


Figure 4. The appearance of polycrystalline and monocrystalline solar cells (Tindo Solar, n.d.).

Monocrystalline cells have been the most efficient since their inception, with a laboratory efficiency of 26.7%, compared to 24.4% for polycrystalline ones (Fraunhofer Institute for Solar Energy Systems, 2021). Moreover, despite their higher price, they dominate the market by far. However, this has not always been the case, as shown in Figure 5.

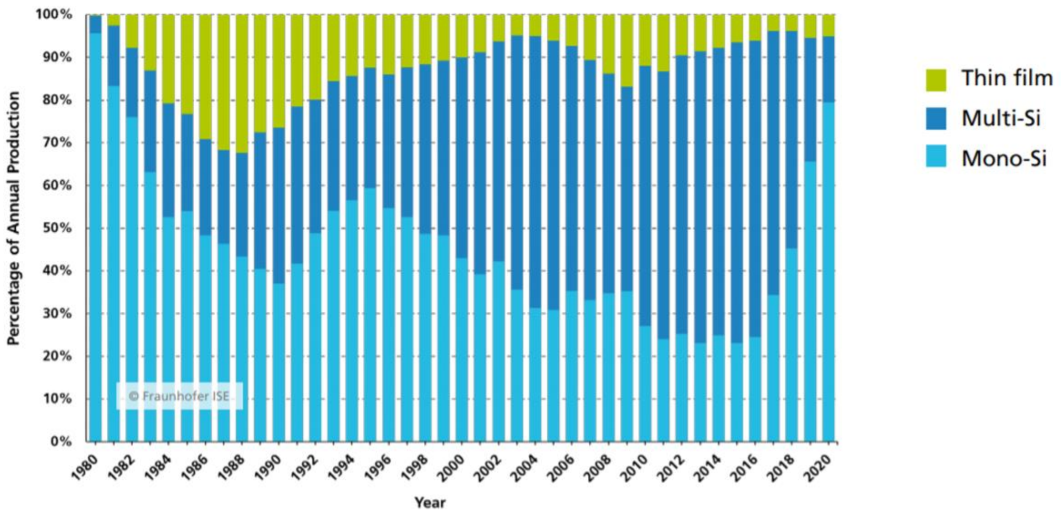


Figure 5. Annual production share of each PV technology (Fraunhofer Institute for Solar Energy Systems, 2021).

Second-generation solar cells

Also known as thin-film cells, they were the second ones to be developed. One of the main characteristics that defines these cells is their thinness: while a wafer-based cell has about 350 µm, a thin-film cell is usually about 1 µm thick (Rathore et al., 2019).

When compared to c-Si, their prices are more competitive while their efficiencies are slightly lower. In addition, they have a significantly better capital efficiency and carbon footprint (Beck, 2020). Furthermore, particular features make them very attractive for the BIPV sector, such as their flexibility and their completely homogeneous appearance.

As shown in Figure 5, only 5% of the global PV production corresponds to this technology. However, according to the study carried out by Frontini et al. (2015) with real projects, in BIPV its market share ranges from 8% in façade integration to 15% in roof integration. This increases to 29% and 22%, respectively, if projects with mixed or hybrid technologies, including thin-film, are considered.

Third-generation solar cells

Also known as emerging PV, this is a relatively recent grouping of technologies aimed at achieving more competitive prices and higher efficiencies than first- and second-generation ones (see Figure 6). Precisely, it is believed that they have the potential to exceed the Shockley-Queisser limit of 33.16% of efficiency (Rühle, 2016).

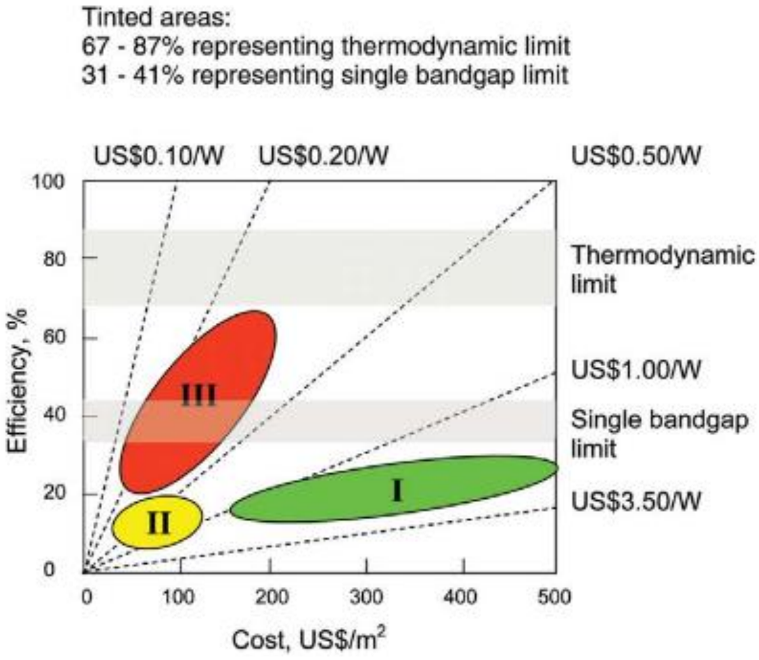


Figure 6. Efficiencies and cost projections for first, second, and third-generation PV cells (Conibeer, 2007).

The main types being developed are:

- Quantum dot solar cells (nanocrystal based)
- Organic solar cells
- Dye-sensitised solar cells
- Perovskite solar cells
- CZTS solar cells

All of these cells mentioned so far are known as single-junction, as they consist of a single p-n junction. However, there is a method known as multi-junction, in which several p-n junctions of different semiconductor materials are joined together in the same cell. This allows them to absorb a wider spectrum of sunlight, making them the most efficient PV cells to date (see Figure 7).

Another kind of PV cell that also aims to achieve higher energy outputs is the bifacial cell. As their name suggests, they are able to absorb energy and produce electricity from both sides.

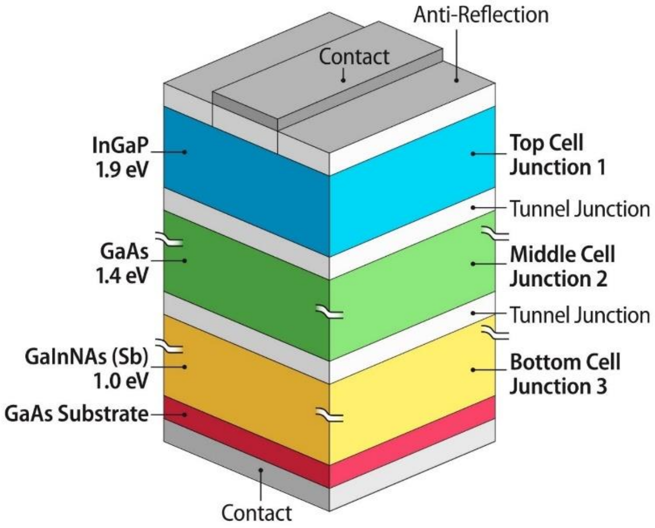


Figure 7. Diagram of a random multi-junction cell with three junctions (Keeping, n.d.).

To complement the information below with images and more data go to Table_Apx 1.

3.1.3 Factors that affect the energy yield in BIPV

Several factors affect the power output of BIPV devices. The following are some of the most relevant ones.

Location

The amount of sunlight received over the year depends to a large extent on the geographical position of the installation. This is not only due to the influence of latitude on the intensity and angle of attack of solar irradiance, but also due to seasonal variability or the climate of the location, among others.

Tilt and orientation

Another crucial factor is the angle at which the solar irradiance hits the cells. This irradiance is made up of direct and diffuse components. As their names indicate, the former is the one that hits the surface directly from the sun, and the latter comes through other elements such as clouds and haze. Most photoelectric output comes from direct irradiance, so the more perpendicular to the sun, the better. For this, both orientation (or azimuth angle) and tilt must be taken into account.

To begin with, the PV modules should ideally be oriented towards the equator. For example, if the installation is located in the northern hemisphere, it should face south.

As far as the tilt angle is concerned, there are several techniques used for its calculation. Although it is sometimes equated with the angle of the site's latitude, the most common is to favour production in the summer months, as this is when there is more irradiance (in the northern hemisphere). In these months, the sun is usually at a greater inclination than that of the latitude (see Figure 8), so the common thing is to subtract between 15º (Sandhu, 2021) and 20º (Roberts and Guariento, 2009) from this angle. This makes more sense if the installation is grid-connected, since in this way if there is a surplus, it is fed into the grid.

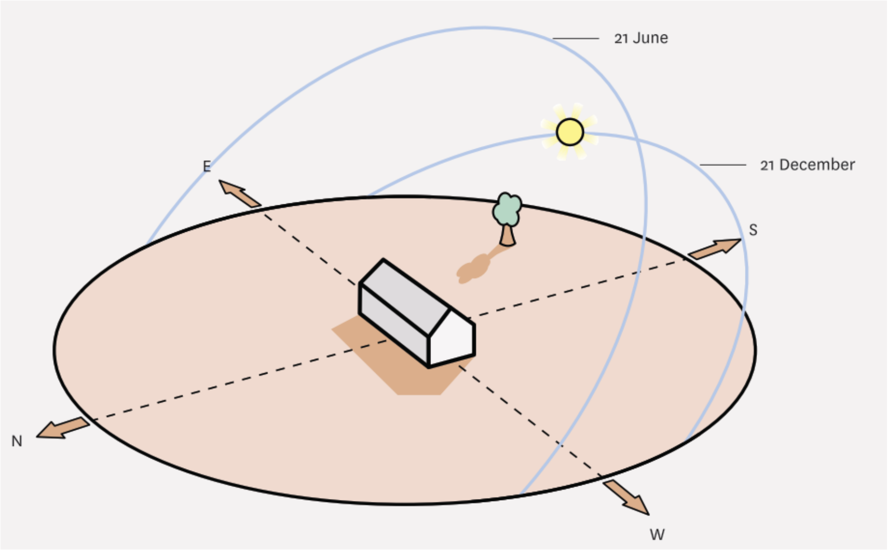


Figure 8. Sun path for both winter and summer solstices in a northern latitude, such as Europe (Roberts and Guariento, 2009).

It should be noted that in BI, it would be necessary to consider and adapt to non-optimal orientations, especially in existing buildings. In these situations, devices composed of thin-film cells perform better than c-Si cells, as they make better use of non-perpendicular and diffuse irradiance.

Overshadowing and partial shading

One of the main problems that can occur in the production of photoelectric energy is shading. Although the concept is the same, two different shading situations are possible.

One of these is overshadowing, which occurs when a large object, usually neighbouring buildings and trees or other parts of the same building, casts a relatively large shadow on the BIPV installation (see Figure 9). In this case, the modules are partially or entirely covered, and the output is significantly reduced. The positive side of this situation is that the shadows can be predicted since the objects are large and usually immobile. For this purpose, it is crucial to carry out 3D modelling of the evolution of these shadows throughout the year, taking into account both existing and planned future obstacles.

The other problematic phenomenon is known as partial shading. It is basically the same but occurs when small or distant elements cause a shadow that covers a small part of the module (see Figure 9). The problem with this situation is that it is caused by leaves and small pieces of debris or cables, making it more unpredictable. And although it may seem otherwise, the decrease in electricity production can be substantial depending on the photovoltaic technology and the PV array configuration used.

Typically PV cells are connected in series within each module so that the voltage is not too small and the current does not increase too much. However, the disadvantage of this is that if one of the cells is partially or entirely covered, the output of all cells in the string is reduced proportionally. When the same current passes through all the cells, its value is set by the one with the lowest output. So for example, if a module usually consists of 36 cells (Honsberg and Bowden, n.d.) and one of them is producing at 50% of its capacity because of a leaf, the production of the module will also be reduced to 50%, even if the rest of the cells can produce at 100%.

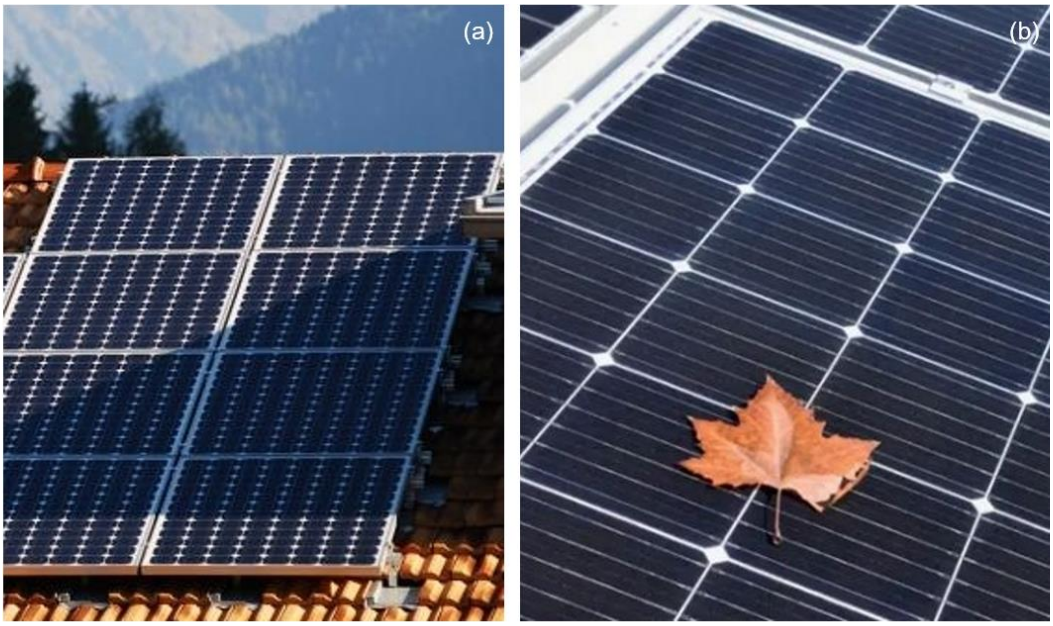


Figure 9. a) Overshadowing caused by a nearby house (PVEasy, 2017); b) partial shading caused by a leaf (Maxeon US, n.d.).

Soiling

Similarly to shading, the accumulation of dust, dirt and other atmospheric pollutants can lead to production losses of between 5% and 17% (Vidyanandan, 2017).

Temperature

Something that also dramatically affects PV production is the temperature that the devices themselves can reach. As mentioned above, most BIPV products in use convert around 20% of solar irradiance into electricity. This means that some of the remaining irradiance is reflected, but most of it is absorbed as heat. This is why these devices can reach temperatures of up to 70 ºC (Roberts and Guariento, 2009).

Calculating the potential reduction in electricity output is relatively easy thanks to the temperature coefficient, which indicates by what percentage the electricity output is reduced (from the nominal value, usually at 20 ºC) for each °C increase in temperature. According to Adeeb, Farhan and Al-Salaymeh (2019), while the values of this coefficient are usually around -0.4 %/ºC for c-Si cells, in the case of thin-film cells, this value is usually slightly higher than -0.2 %/ºC.

BIPV devices must be ventilated to combat the temperature effect. To this end, whenever possible, a gap should be provided between the building and the module to facilitate airflow. Needless to say, the wind also helps in this process.

3.1.4 Possible uses of BIPV

The energy generated by PV devices is nearly always used to power any electrical system in the building, from lighting to household appliances.

However, this energy is sometimes used to produce heat through electrical devices. A clear example is that of electric water and air heaters, which can serve as a backup. Their use should be considered only in well-insulated buildings with low energy consumption. Another possibility is using PV electricity to supply heat pumps for indoor space heating and cooling and water heating. These pumps can exchange heat from external air (air-to-air and air-to-water heat pumps), from external water (water-to-water heat pumps) or from the ground (geothermal heat pumps) (Becker et al., 2017).

3.1.5 BIPV products

Considering the different characteristics of the BIPV products offered by manufacturers, they can be classified into four main groups. Actual projects where these products have been used are shown in the Table_Apx 2 and Figure_Apx 1.

Foil products

They are the most flexible and lightweight products on the market, allowing them to adapt to non-flat surfaces and making them suitable for surfaces with relatively high weight limitations. These products are usually made of thin-film cells due to their features, as mentioned above.

Tile products

As one of the most common roof elements, tiles have great potential as PV generators. That is why there is a wide range of BIPV products that accurately imitate these elements. As with regular roof tiles, both flat and curved options are available. The latter, while not as effective at collecting irradiance as the former, is often more aesthetically pleasing. In this case, it is common to find products with both c-Si (usually for flat tiles) and thin-film (for both flat and curved tiles) cells.

Module products

It is a very similar product to the standard PV modules, with the only difference being that they have to satisfy all the functional and constructive requirements for the BI to take place (just like the rest of the BIPV products). In this case, it is also common to find both c-Si and thin-film cells, depending on surface conditions and location.

Cell-glazing products

While a large part of building surfaces are opaque, a significant portion comprises translucent elements such as windows or other glazed parts of façades and roofs. While the above products are suitable for opaque parts, solar cell-glazing products are perfect for translucent parts. These products are ideal for controlling the amount of sunlight entering the building. There are two techniques to achieve transparency:

- To space the cells from each other and place them in a module with glazed plates on both sides.
- To use materials that allow a substantial amount of sunlight to pass through. These are currently under research and development (see Chapter 6.4).

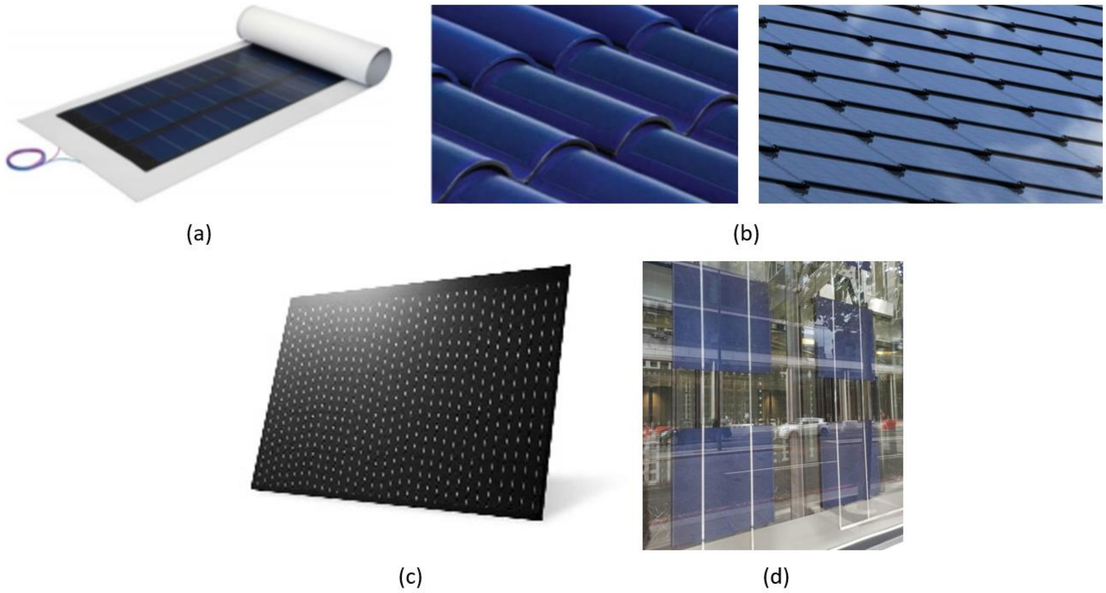


Figure 10. BIPV products (Jelle, 2016): a) BIPV foil, b) BIPV tile, c) BIPV module, d) BIPV cell-glazed.

3.1.6 Possible ways of integrating BIPV products into buildings

In this section, a summary of the different integration options of BIPV products has been carried out based on the surfaces on which this process occurs, mainly roofs and façades (see also Table_Apx 2 and Figure_Apx 1).

Roof integration

Since the beginning of the Building Integration technique, the desired surface for most architects and builders has been the roof. As shown in Figure 11, it is usually the surface with the highest solar potential due to its position and orientation.

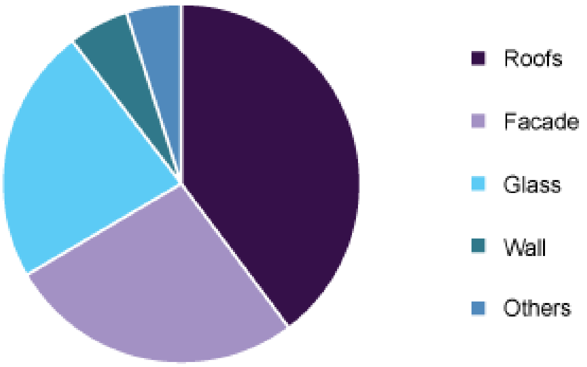


Figure 11. BIPV market share in Europe in 2019 by application. (GVR, 2020)

There are many possible options with the products described in the previous section. As a clarification, cases where cell-glazed products are used are referred to as atriums or skylights.

The most common roofs are usually those with a flat surface. For products containing c-Si cells, as already mentioned, the most suitable are those with a slope that allows them to face the sun. If the inclination is not appropriate or is even wholly horizontal, thin-film technology is a better option. The inclination of these surfaces is also important in terms of architectural integration. In projects with roof integration in which the slope is very small or non-existent, as they may not be visible from the ground, their impact on the aesthetics of the building is negligible.

The situation is quite similar in curved roofs, which, if correctly oriented, can achieve high efficiencies, although usually not as high as flat ones. The most suitable products for these surfaces are generally thin-film cells due to their flexibility, although first-generation cells can also take some curvature as long as it is not too steep.

Finally, a typical roof, especially in industrial buildings, is the saw-tooth shaped one. Thanks to its inclination, it can achieve results as good as those of pitched roofs. In addition, if translucent, it offers an excellent daylighting option for the interior of the building and, at the same time, avoids excessive direct lighting and heating.

Façade integration

Despite their poorer orientation than roofs, the potential of the facades of conventional buildings is quite significant. Furthermore, these surfaces can have significantly higher potentials in high-rise buildings such as skyscrapers than the roof. This is further enhanced in high latitude locations, as the sun’s elevation throughout the year is often low.

Once again, in addition to the height of the building and the latitude, a determining factor in energy performance is the inclination of the façade. Although it is complicated to have the façade tilted enough to face the sun, the closer it gets, the better the energy yield of the installation.

Because of this generally unsuitable inclination, products composed of second-generation cells are the most suitable. Furthermore, shading tends to be higher on facades. It is precisely because of the increasing importance of facade integration in the field of BI that this type of PV technology is expected to boom in the next few years if the right conditions are met.

However, it should be noted that in high latitudes such as Europe or North America, currently the main markets for BIPV products, c-Si cells, offer efficiencies good enough to continue to dominate the market due to the low altitude that the sun reaches most of the year.

A significant part of façades often consists of translucent elements such as windows, so cell-glazed products have great potential too. It is even more common in large cities, where glass facades completely cover many high-rise office buildings. Following this trend, curtain walls are becoming more and more common in new buildings. These are self-supporting structures adjacent to the main building. In addition to protecting the building from the weather, they provide a more aesthetically avant-garde look. Moreover, if ventilated, they regulate the temperature inside the building thanks to the airflow generated and improve the performance of the BIPV devices (Fuentes, 2007). This is undoubtedly a very interesting technique to combine with solar devices.

Other integration options

These include structures that are independent of both the roof and the façade but which are in some way connected to them. A clear example are balconies, which in a way offer the same possibilities as vertical facades.

Another very interesting structure are sunshades. These inclined structures are usually placed over windows. As with saw-toothed roofs, they block most of the direct radiation and prevent the indoor space from overheating. And thanks to their inclination, if covered with BIPV products, they enable a better energy yield.

3.1.7 Storage options and their integration

When a building or dwelling owner decides to install batteries to store the surplus electricity produced and use it during off-peak hours, their integration is also considered. While some batteries are weather-protected, they are usually located under cover or indoors. This is why it is important to always check that the available space can accommodate such batteries, both in terms of weight and size. It is worth mentioning that the most commonly used are lithium-ion and lead-acid batteries.

Another way of storing the energy produced is by heating a water tank with electric heaters (Becker et al., 2017). However, this technique is rarely used, as the capacity of BIPV devices to heat water is much lower than that of BISTs.

3.2 Building-Integrated Solar Thermal (BIST)

Whether due to lack of knowledge, interest or support, ST energy has not experienced the same development and growth as PV. In the BI sector, the disparity is even more significant. However, its potential is enormous. Its high efficiency, simplicity, and high heat demand of buildings are the main reasons to justify it.

Precisely, according to Ürge-Vorsatz et al. (2014), if the energy consumption of residential buildings is divided by end-use at a global level, approximately 56% corresponded to some form of heating in 2010 (58% if cooling is taken into account). This value was somewhat lower in commercial buildings, reaching 45% (or 52% with cooling). If areas such as Europe or the United States are considered, with very high energy consumption and higher heating requirements due to their latitudes, these values increase to 68 % in residential buildings in the former (European Comission, 2013) and 62% in the latter (US Energy Information Administration (EIA), 2015).

3.2.1 Basics of ST

Its operation is quite simple, especially when compared to PV technology. In essence, it consists of capturing solar irradiance through a collector. This element converts that energy into heat and transfers it to a fluid to be transported and stored in a tank for later use.

When speaking of ST energy, it usually refers to low-temperature energy. This means that the fluid that absorbs and transports the heat does not usually exceed a temperature of 100 ºC, although it can occasionally reach 150 ºC (UNEP, 2014).

3.2.2 Technologies used in BIST

One of the most important factors to consider is the absorber material, as it has to achieve the highest absorptivity and the lowest reflectivity and transmissivity possible. Usually, metals with good conductivity are used, such as copper, aluminium and steel. In addition to this, dark colour coatings are used to increase the absorption capacity of the receiver, black being the best choice (Boyd, 2010). This allows efficiencies of over 90% to be achieved, although at average working temperatures, it is usually around 60-80% (Figure 12).

Another thing to consider is the fluid used to absorb, transport and store the heat (Jingchun Shen et al., 2015). The most commonly used one is water, thanks to its high thermal capacity and conductivity, and low viscosity and cost. It’s usually mixed with glycol when there is a danger of freezing. It is suitable for direct domestic water heating or indirect space heating.

Another common fluid is air, which doesn’t pose a risk of freezing or boiling despite its lower thermal capacity. Moreover, it’s not corrosive, it’s cheaper, and can be used for direct space heating. Other BIST systems are based on refrigerants such as CFC and HCFC. These have higher thermal capacities than water, lower freezing and boiling temperatures and lower viscosity. Finally, the most recent fluids to gain interest in this field are PCMs, which offer higher density energy storage and the ability to operate over a wide range of temperatures (Mofijur et al., 2019).

As for the devices used for heat collection, three are the most commonly used:

Flat-plate collector

This is the most common type of collector, and it’s usually employed for water and space heating (best suited for applications demanding 30-70 ºC, up to 100 ºC) (see Figure 12).

This technology consists of a metallic, wooden or polymeric box, with an insulation plate on one side and a translucent plastic or glazed plate on the other. In the middle, the absorber (a flat dark-coloured plate) is placed, and the heat, once absorbed, is transferred to the tubes inside the collector. The irradiance enters the box through the glazed plate, while the insulation plate avoids the irradiance to escape. The glazed plate also insulates the cage as it protects the collector from the outside wind, which causes a lot of losses due to convection.

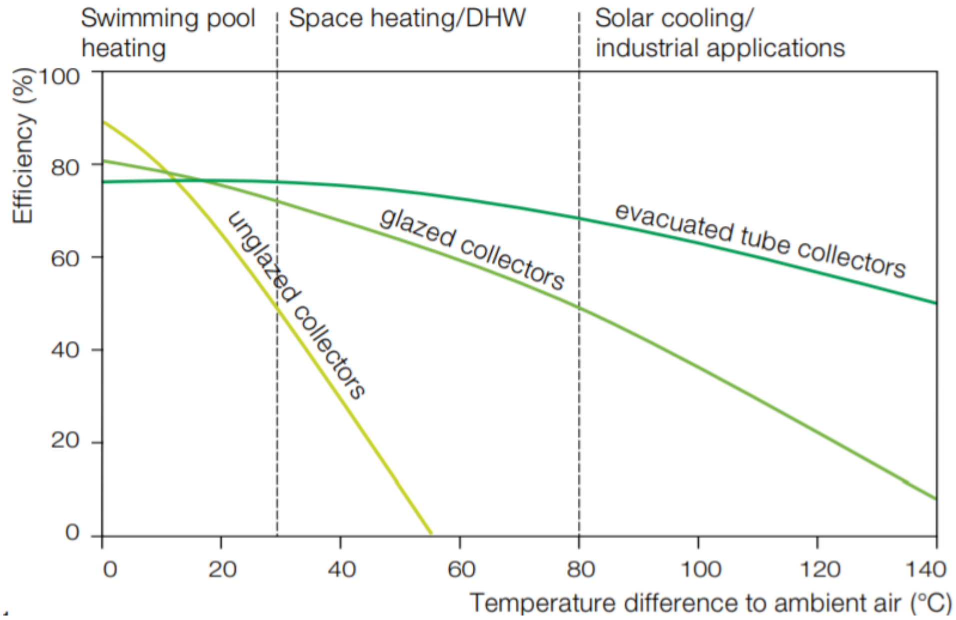


Figure 12. Efficiencies of different types of collectors according to the working temperature and application (Munari Probst and Roecker, 2011).

Unglazed collector

Conceptually it is the same as the flat plate collector but without the glazed plate. Due to that absence, there is no insulation on that side, and the obtained temperatures are lower, as well as efficiency. Their working range is usually 10-50 ºC, easily reaching 60-65 ºC. They are mainly used for swimming pool heating, and also for low-temperature space heating and DHW pre-heating (Munari Probst and Roecker, 2011).

A positive aspect of the lack of a glazed plate is the greater ease with which it can be better integrated architecturally. In addition, it is cheaper as it has fewer components.

Evacuated-tube collector

It consists of a set of glazed tubes with a collector inside, where the space between them is vacuumed. Thanks to the great insulation of vacuum, this is the BIST technology that achieves de highest temperatures (80-140 ºC), even in cold climates. It is typically used for domestic water and space heating, but also for industrial heating.

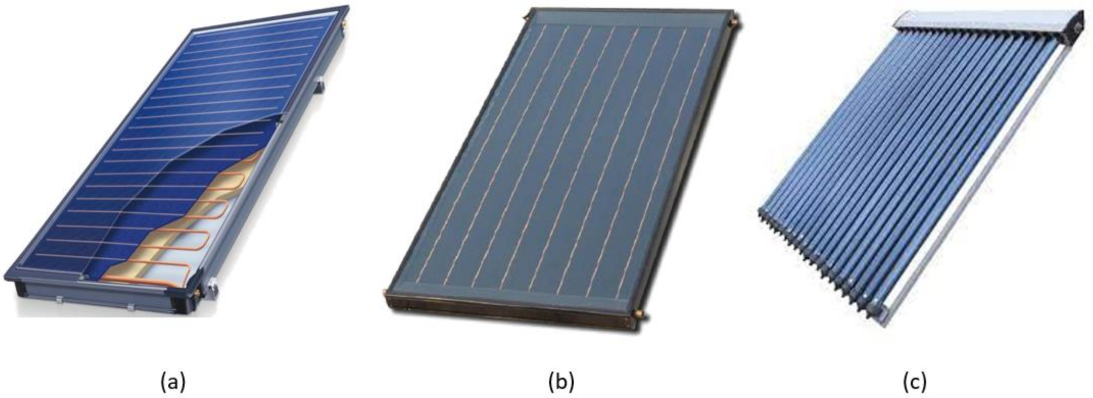

(a) (b) (c)

Figure 13. (a) flat plate collector, (b) unglazed collector, (c) evacuated-tube collector.

3.2.3 Factors that affect the energy yield in BIST

Even if some factors affecting energy yield in BIST are similar to those in BIPV, there are some important differences.

Location

This factor is equally essential in BIST, as the amount of solar irradiance received depends on it to a large extent.

Tilt and orientation

To have a good energy yield, as with c-Si cells, ST collectors need a good orientation towards the sun.

Overshadowing and partial shading

Even if overshadowing is still a big problem with this technology, partial shading is not as problematic as with PV. If a portion of a solar collector is covered, that portion won’t absorb as much heat as usual, but the rest of the collector will work as expected. Hence the reduction in production will be lower.

Temperature

One of the main differences is with temperature, as its effect is entirely the opposite. The hotter the collector, the higher the heat production. However, the thermal limits of every component in the device must be taken into account, although the temperatures they withstand are usually much lower.

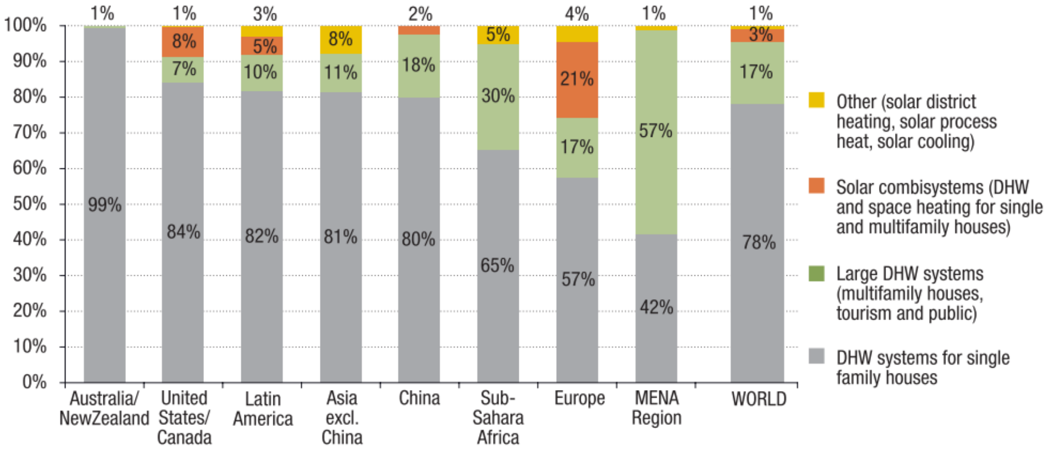
Wind

This meteorological phenomenon has a major negative impact, especially on unglazed collectors (Burch and Casey, 2009). A large part of the heat loss from this kind of collectors is the result of the convection it causes. It is essential to know the actual wind distribution over the whole surface. It’s not enough with the average velocity, as the direction from where the wind comes matters too. If the wind speed is low, the convection will be natural. But as the speed grows, that convection will turn into forced, making losses much bigger. According to Ladas, Stathopoulos and Rounis (2017), the loss in efficiency can reach values of almost 50%.

With flat plate collectors and evacuated-tube collectors, as a glazed plate covers the collector, the impact of wind on the energy yield is much lower.

3.2.4 Possible uses of BIST

The main application of BIST devices is DHW, with temperatures from 40 ºC to 65 ºC needed (Maurer, Cappel and Kuhn, 2017). As shown in Figure 14, in the case of flat plate collectors, 95% of the installations had this use in 2011 worldwide. Only 3-4% were used for space heating and 1% for other applications such as cooling or industrial heating (UNEP, 2014). However, it can be seen that in certain areas such as Europe and North America, applications like space heating are becoming more relevant.



Asia excluding China: India, Japan, Taiwan

Latin America: Brazil, Mexico

Europe: EU18, Albania, Norway, Switzerland, Turkey

MENA Region: Israel, Jordan, Lebanon, Tunisia

Figure 14. Distribution of flat plate collectors by application and region in 2011 (UNEP, 2014).

Other types of water heating are also possible, such as swimming pool heating or industrial process heating.

The second most common application is space heating. However, due to the temperature difference between the heat-transmitting fluid and the ambient being relatively high, efficiencies are pretty low in this application. That’s why it’s recommended to combine it with other types of heating (Maurer, Cappel and Kuhn, 2017).

Other possible applications are dehumidification or cooling, the latter being carried out by heat pumps, especially in industrial applications with great cooling demand.

3.2.5 BIST products

One way to classify BIST products is by the light they allow to get through. Thus there are opaque products on the one hand and translucent products on the other (see Table_Apx 3 and Figure_Apx 3 to see real projects).

Opaque products

In contrast to BIPV products, the dimensions and shapes of BISTs are not as constrained. Due to the simplicity and abundance of materials used in the components of these products, it is very easy to make them in different sizes and even curved shapes. Even so, given that it is still a rather small market compared to BIPV, the options are not so numerous.

Tile-shaped products are quite common. These are usually offered in both flat and curved shapes, and options are available with all three BIST technologies mentioned. The most common ones are the flat ones, made of unglazed and glazed flat plate collectors mainly. Curved-shaped collectors are usually obtained by putting a curved glazed plate into a flat-plate collector or with evacuated tubes.

Modular products, aesthetically similar to BIPV modules, are also common. These are mainly composed of flat plate collectors.

In addition to these two quite distinctive forms, opaque products can take a range of different shapes. It is somewhat common to find products, mainly composed of unglazed collectors, which act as complete roof or façade covers.

Translucent products

These products offer the possibility of allowing daylight to enter the interior of the building. One of the possible options is to use evacuated-tube collectors, adding one or two glazed covers to act as a protecting layer for the interior. Another option is to use flat-plate collectors by replacing the insulating plate with a glazed one and dividing the absorbing plate into several sections, thus allowing the light to pass through. This latter option would entail a considerable decrease in efficiency.

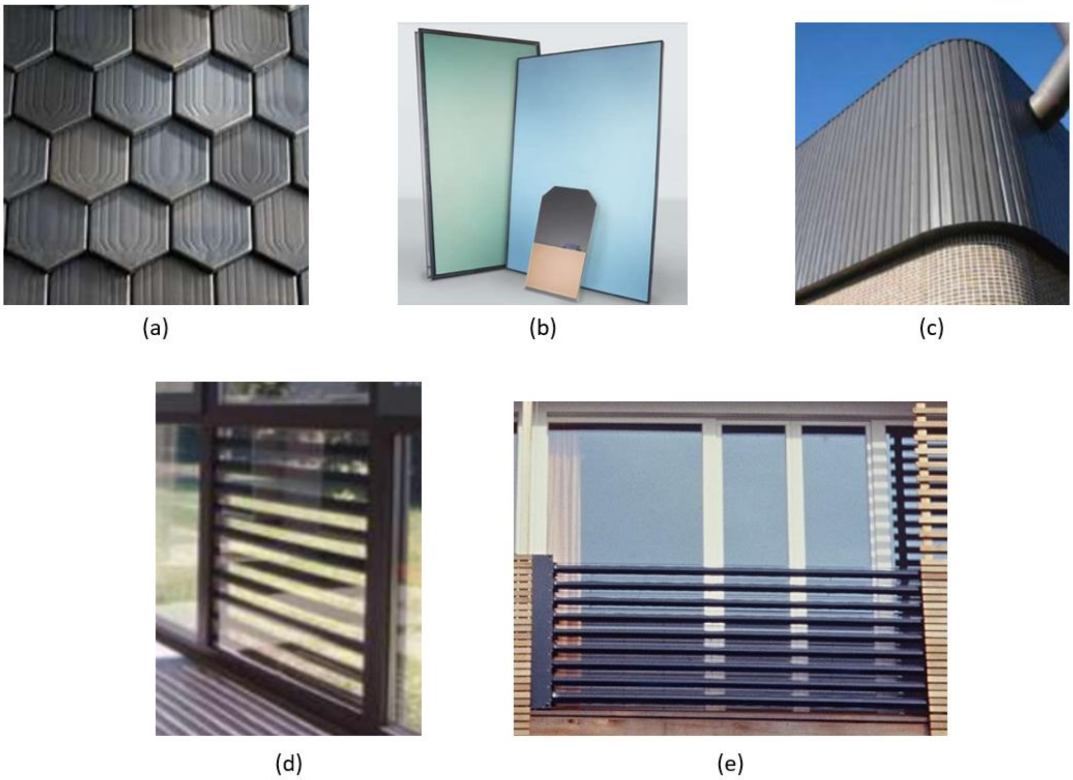


Figure 15. a) opaque unglazed tiles, b) opaque flat-plate modules, c)opaque unglazed cover, d) flat-plate translucent module, e)evacuated-tube railings.

3.2.6 Possible ways of integrating BIST products into buildings

The ways in which BIST products can be integrated into buildings is quite similar to BIPV. They are mainly integrated into roofs and facades, the main surfaces of buildings (see also Table_Apx 3 and Figure_Apx 3).

Roof integration

This is the surface of the building with the highest potential, as already mentioned. But it’s usually also the most exposed to weather conditions, such as rain and wind, which can affect the energy yield considerably.

The ideal roof would be pitched to an angle where the sun is facing directly to the surface, as it happens with the c-Si in the BIPV market. However, if the surface angle is too far from ideal, no alternative works well, as with thin-film in BIPV. This is why completely horizontal roofs are not suitable in regions far from the equator. The collectors are usually installed on inclined structures on such roofs, which cannot be considered BI but rather BA.

Although it would be logical to always use flat plate collectors on this surface due to their greater protection against wind, among other factors, the enormous capacity for aesthetic integration offered by unglazed collectors makes them very attractive too.

Façade integration

A positive aspect of the integration of BIST products in façades is that, when the demand for heat is the highest (in winter), the façades are well positioned to produce heat with the collectors. This is due to the low altitude of the sun, especially at high latitudes. Thanks to this, the heat production can be kept relatively constant throughout the year, making it quite attractive (Ghitas, 2012).

Moreover, although the angle may not be the best at certain times of the year, considering that the shading does not affect it as much as BIPV, it is arguably more suitable for these surfaces (Ghitas, 2012).

Usually, flat plate collectors and unglazed collectors are used for opaque sections, and evacuated-tubes collectors and sometimes flat plate collectors for transparent parts.

Other integration options

A popular option, in this case, is the integration into balconies. Although BIST modules can also be used as opaque balcony railings, it is more common to use evacuated tubes as balcony railings, providing transparency.

As in BIPV, sunshading is also possible, although it is less often seen. There are different options in this case, offering options with total and partial shading.

3.2.7 Storage options and their integration

While in the case of BIPV storage is optional, in the case of BIST it is necessary. If the heat generated is not needed at the moment, there is no other option but to store it. Usually, a tank is used to store the fluid used, which must be correctly dimensioned depending on the size and number of collectors. These cylindrical-shaped tanks need a surface that provides good insulation. It would be ideal to place these tanks inside buildings to avoid further heat loss (see Figure 16), but their size and shape make this complicated. Therefore, if the tank is located outside the building, its aesthetic impact should also be considered.

Systems that use unglazed collectors to heat swimming pools do not need a storage tank, as the pool itself functions as storage.

Figure 16. Integration example of a water tank inside a residential house (Kalogirou, 2015).

3.3 Building-Integrated Concentrating Systems (BICS)

This technique can be used to increase the productivity of either a PV cell or a ST collector. While it is true that it has been known for a long time (especially CST, also known as CSP), its large-scale expansion has not yet taken place. By the end of 2020, CST energy had 6.475 GW installed worldwide (IRENA, 2021), practically all in large-scale installations. This represents only 0.9% of total installed solar power (IRENA, 2021).

The situation for CPV is even more residual, with only 358 MW installed worldwide in 2015 (Tiwari, 2016), just 0.16% of the cumulative solar power installed that year (IRENA, 2021). Estimates suggest that by 2020 this capacity would have multiplied to more than one GW installed (Tiwari, 2016), but this growth would still be lower than that of conventional PV. While it is true that in the case of CPV, most of the installed equipment corresponds to large installations as well, it is becoming more and more common in the BI sector, especially if we compare it with BICST.

3.3.1 Basics of BICS

The working principle of these devices is quite simple: to use a reflecting or refracting surface to concentrate the solar irradiance on a smaller surface. Concentrating systems are usually classified according to how much solar energy they concentrate. To quantify this magnitude, two common scales are utilised.

One of the options is to use the magnitude known as “sun”. This corresponds to the average solar irradiance incident on the earth at AM 1.5G condition and corresponds to a value of 1000 W/m^2 (Jeong, 2009). Therefore, the amount of “suns” the concentrator achieves represents how much it has multiplied that energy value.

Another way of measuring it is known as the concentration ratio or C. This constant is calculated by dividing the concentrator aperture area A_1 by the receiver area A_2 (Gajbert, 2008).

Concentrating systems perform best when they have a tracking system to obtain the best orientations throughout the day. This is especially important in systems with medium and high-concentration ratios (C > 10X and > 100 X, respectively).

However, these systems are usually not compatible with BI, so stationary concentrators are commonly used. Generally, concentrators with a C < 5X do not need a tracking system (Luque and Viacheslav, 2007), and for those with a C < 10X, a single-axis tracking system is usually sufficient (Gajbert, 2008).

However, static concentrators with higher ratios using luminescent and photonic crystals are expected to appear (Luque and Viacheslav, 2007).

The main benefit of these devices is the space and material savings compared to non-concentrating systems. In other words, to achieve the same result, less surface area of PV modules or ST collectors is needed thanks to the higher concentration of irradiance (Chemisana, 2011). Moreover, considering that the materials of which the reflectors/refractors are composed are cheaper, especially compared to PV devices, the savings are substantial (Li et al., 2020). According to Mallick and Eames (2007), a BICPV device can lead to a cost reduction of up to 40% compared to a BIPV device.

The main disadvantage to mention is the difficulty of integrating them in buildings, mainly due to their shape and size but also because of the aforementioned need for a tracking system for devices with a high concentration ratio. Another negative aspect is that they may overheat considerably, so adequate cooling is necessary.

3.3.2 Technologies suggested and used in BICS

Numerous types of concentrators can be used in BI concentrating systems, but here are some of the most commonly used or suggested ones in existing projects and designs.

But before starting with the different types of concentrators, let’s briefly mention what materials they are usually made of. Reflectors are mostly made of aluminium (at least the reflecting surface) due to its good reflectance (up to 87%), manufacturing flexibility and low cost (Gajbert, 2008). On the other hand, refractors are usually made of high-tech plastics, although in the past the predominant material was glass (Seltman, 2020).

Flat reflectors

The principle of operation of these reflectors is quite simple. Being flat, if a group of parallel rays hit the mirror, they will bounce off in a new direction but remain parallel.

The simplest way to use these elements to concentrate energy is to use them to redirect rays that were not directed towards the solar device in the first place, as shown in Figure 17. The downside of this is that the redirected rays arrive at a non-ideal angle of incidence, which will negatively affect the device's performance, especially for c-Si modules. For ST it’s not ideal either, but research shows that the increase in the output can reach 25% in summer (Tripanagnostopoulos, 2014).

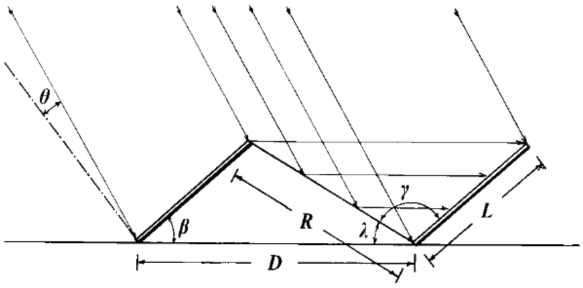


Figure 17. Example of flat mirrors installed next to ST collectors (Tripanagnostopoulos, 2014).

Another option with this type of reflectors are the V-trough mirrors. As shown in Figure 18, in addition to the beams that fall directly on the solar device at the bottom of the trough, more of them are concentrated due to the larger aperture surface of the reflector. These devices reach concentration ratios of up to 3X, but for that, a tracking system would be required (Gajbert, 2008), which in most cases would negatively affect the integrability of these devices.

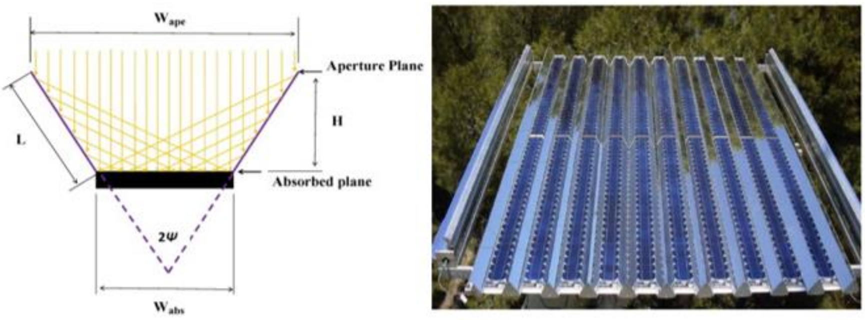


Figure 18. a) 2D representation of how rays strike and reflect in a V-trough (Al-Shohani et al., 2016). b) Picture of a real solar collector with V-trough mirrors (Hermenean, Visa and Diaconescu, 2009).

Parabolic reflectors

The application of parabolic reflectors is very interesting, as any beam incident parallel to the optical axis will be concentrated at the focal point.

One of the most common variants is parabolic troughs, which are widely used in large-scale solar installations. Being a parabolic-shaped trough, the multiple focal points of each section form a focal stripe, in which the solar receiver is placed. The use of a tracking system is essential in such devices, as the incident angle of the solar irradiance is very important. These devices can achieve medium concentration ratios, but only if the concentrator-receiver set is able to track the sun. This condition makes their integrability in buildings rather limited.

Another popular option is the Compound Parabolic Concentrator or CPC. This is a non-imaging concentrator consisting of two parabolic dishes facing each other. Any ray arriving within the acceptance angle of the collector will be reflected several times until it ends up on the absorber surface at the bottom of the CPC (Bohg and Briska, 2014).

One of their main advantages is that they can accept incident radiation over a relatively wide range of angles, usually from 10º to 80º. As a result, they can collect part of both direct and diffuse irradiance. Furthermore, although it would improve their efficiency, they do not require a tracking system, which makes them very attractive for building integration. In these cases, their concentration ratio is low (< 5X) and they reach temperatures suitable for low and medium-temperature applications (up to 200 ºC) (Orosz and Dickes, 2017).

The absorbers can be configured in various ways, as shown in Figure 19, for both PV and ST. In the case of PV, it is recommended to use bifacial cells (Chemisana and Mallick, 2013). The reason for this is that the uniformity achieved is not particularly good, and under these conditions, monofacial cells do not perform well.

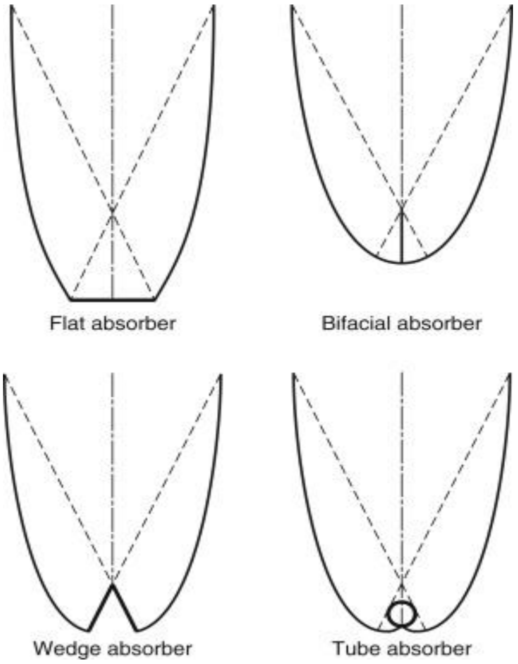


Figure 19. Possible absorber configurations for CPC (Bohg and Briska, 2014).

Fresnel lens/mirror

These concentrators offer a similar alternative to parabolic reflectors but in a more compact way. That is, instead of using ordinary mirrors and lenses, they are composed of small aligned sections of such elements, each with a different tilt. In this way, all perpendicularly incident rays are concentrated at the focal point (see Figure 20).

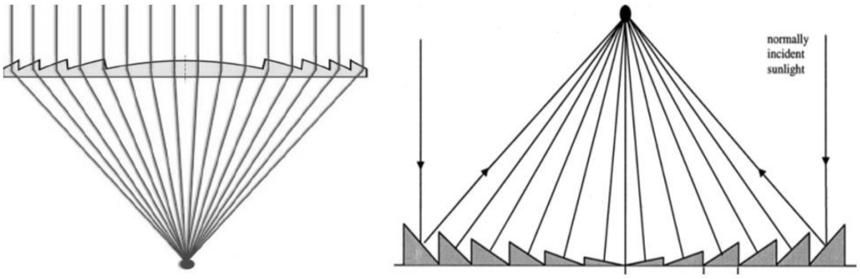


Figure 20. Schematic representation of Fresnel lens (left) and mirror (right).

This results in an effective concentrator using considerably less material and space. As with parabolic troughs, they achieve medium-concentration ratios, provided there is a continuous tracking system. Unlike parabolic troughs, however, they offer the possibility of achieving low concentration ratios by using static concentrators and mobile receivers that track the sun on one axis. This latter option enables better building integrability (Chemisana and Mallick, 2013).

Luminescent solar concentrator

Although it was first proposed in 1976, it is a type of concentrator that is gaining more and more attention due to its features. The LSC is composed of a polymeric or glass waveguide which in turn is covered with chromophores or luminescent dyes. When sunlight strikes the waveguide, the chromophores absorb it and re-emit it at a longer wavelength. This radiation is trapped inside the waveguide and by internal reflection is guided to the edges, where the PV cells are located as shown in Figure 21 (Meinardi, Bruni and Brovelli, 2017).

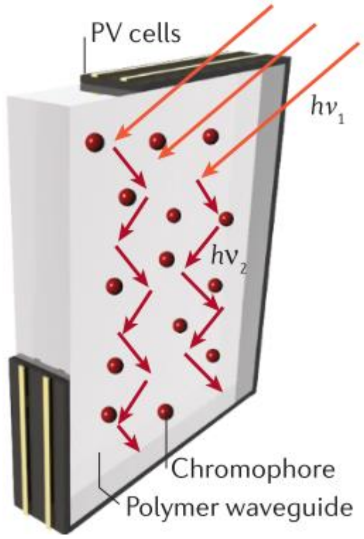


Figure 21. Schematic picture of the working principle of a LSC (Meinardi, Bruni and Brovelli, 2017).

One of the main advantages is that the part of the irradiance that is not absorbed passes through the waveguide, making it semi-transparent. In addition, it can absorb both direct and diffuse irradiance, so it does not need a tracking system and is not affected by shadowing effects or the position of the sun relative to the device (Meinardi, Bruni and Brovelli, 2017). These properties make it very attractive for integration in buildings, especially in glazed facades or windows.

However, the difficulty in synthesising chromophores has slowed down the development of these concentrators. Even so, many are being researched, and among them, quantum dots are one of the most promising. Thanks to the nanoscopic size of their crystals, they have a greater capacity to absorb solar energy (as it happens with quantum dot PV cells). This allows an LSC with quantum dots to reach concentration ratios of 5-10X (Purcell-Milton and Gun'ko, 2012).

To have a better idea about these components and their possible applications go to Table_Apx 4 and Figure_Apx 4.

3.3.3 Possible ways of integrating BICS into buildings

Although there are very few active BI concentrating systems, there are numerous prototypes and proposals. The main challenge remains the integrability of most of the suggested designs, as well as their economic viability (take a look also at Table_Apx 4 and Figure_Apx 4).

Roof integration

As has been repeatedly explained, the roof is often the best option due to its location and orientation. But in addition, with these devices being more challenging to integrate, their lower visibility from the outside makes them even more suitable. And despite their generally poorer orientation, flat roofs are the best option in terms of reduced visibility.

In addition to the bulkiness of concentrating systems, another factor that hinders their integrability is the use of tracking systems, as mentioned above. Therefore, options that do not require tracking systems are particularly attractive, such as flat reflectors, but especially CPC and LSC.

One option to make devices with a bigger visual impact, such as CPCs, more aesthetically pleasing is through the use of glazed or polymeric coatings. In this way, they blend in much better with the overall aesthetics of the building. Similarly, numerous designs have been suggested where micro concentrators are introduced into the usual BIST collectors, ranging from Fresnel lenses and mirrors to CPCs.

As for the translucent options available, in addition to LSCs, it may also be possible to use Fresnel lenses.

Façade

Their high visibility from the outside makes it necessary to be more cautious when integrating these devices into façades. However, there are several options among the suggested technologies that can cause minimal visual impact or even enhance it. These include LSCs, asymmetric CPCs, Fresnel mirrors and micro concentrators.

3.4 Building-Integrated Hybrid Systems

Of the irradiance incident on the PV modules, only about 20% is used for electricity production. The remaining energy absorbed or transmitted in the form of heat is therefore lost. One way to utilise this heat is through hybrid devices that integrate features of both PV and ST devices into one product.

The benefits of this increasingly popular technique are numerous. The main one is the higher utilisation of incident energy, especially when compared to BIPV installations. While it is true that BIST products are already offering very high efficiencies on their own, they are often dismissed because of the advantages provided by BIPV products in terms of integration and price. Thus, instead of competing against each other, these two technologies can work together to provide a better result. Moreover, thanks to the absorption of much of the excess heat, the PV cells do not reach such high temperatures, so their efficiency is considerably increased.

The BIPVT solutions offered are generally of two types. One is to place a ST absorber immediately adjacent to the PV module with water as the transmitter fluid (see Figure 22a). In these cases, special care must be taken with the temperature, as the ST collectors can get very hot and negatively affect the PV cells' performance.

This is why the second option is usually the most efficient and the most widely used. It harnesses the excess heat through an air flow, which can be natural or mechanically forced (see Figure 22b). While it is true that a natural air flow may be sufficient to absorb the heat and cool the PV cells, sometimes it is not, and forced ventilation is necessary.

Figure 22. Diagram of a cross section of a) water-cooled PVT collector; b) air-cooled PVT collector (Kalogirou, 2015).

A clear application of this practice is the aforementioned curtain walls, which, if ventilated, are used for both space heating and cooling of the building interior. It can also be applied to other types of roofs and ventilated facades, not necessarily translucent. Moreover, this technique is equally applicable to concentrating solar systems, as shown in Figure 23.

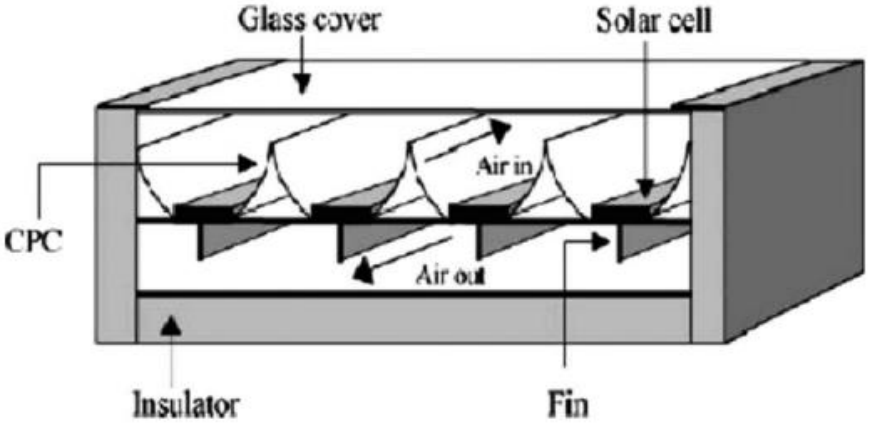


Figure 23. Schematic of a PVT collector with CPC.

More information and images of hybrid systems are available at Table_Apx 5 and Figure_Apx 5.

4 Evaluation of Architectural Integration for BI products

The following is a brief analysis of the most critical factors that determine a good integration architecturally speaking to a large extent. In addition, a comparative evaluation of the BI products will be carried out.

4.1 Installation size and position

The size and position of the installation is a factor that undoubtedly affects the architectural integration. But at the same time, it is conditioned by four other factors:

- Available surface area
- Used solar technology
- Energy production goal
- Architectural needs of the building

Each of these factors directly affects the others, and there is no clear hierarchy as to which of them should be prioritised. In the case of existing buildings that are being refurbished, for example, the factor that conditions the rest is the available surface area, since it cannot be changed. There is often a balance to be made between achieving the maximum possible energy output while maintaining an aesthetically pleasing result.

4.2 Size and shape of the device

This is a very relevant factor because depending on the technology chosen and the options available, the size and positioning of the installation are totally conditioned.

Producers of both BIPV and BIST devices usually commercialise them in standard sizes and shapes. In addition, they are often designed to be integrated into surfaces with specific conditions. However, the variety of options available is significantly greater in the case of BIPV products.

The wider the variety of sizes and shapes of the products, the greater their integrability, as the installation will be better adapted to the aesthetics and requirements of the building. Commercial BIST devices are often very bulky, which makes integration difficult. They also involve the installation of additional elements such as pipes and storage tanks, making it even bulkier.

It is indeed possible to get BIST devices in small and attractive sizes and different shapes, but this means ordering a tailor-made product, which leads to a substantial cost increase.

Usually, “dummy elements” are used to address this problem. These are elements that look like solar devices but do not have any energy-generating technology, and are used on surfaces or spaces for which there is no suitable BI product. In this way, it is possible to customise them more cheaply, thus giving the installation a much more integrated overall appearance.

4.3 Colour

Colour is another factor that is conditioned by energy production targets. The darker the element that absorbs solar radiation, the higher its efficiency. That is why PV cells usually have colours ranging from black to blue, grey or dark brown, and ST collectors and their coatings are traditionally black.

There are ways to obtain PV modules in other colours like green and red, such as by varying the thickness of the anti-reflection coating. However, this leads to losses of 15-30% (Roberts and Guariento, 2009). In the BIST field, absorbers of other colours such as blue, red or green can be easily obtained, and the losses are usually around 7-18% (Tripanagnostopoulos, Souliotis and Nousia, 2000). Even so, the variety of colours in commercially available products is still greater for BIPV products.

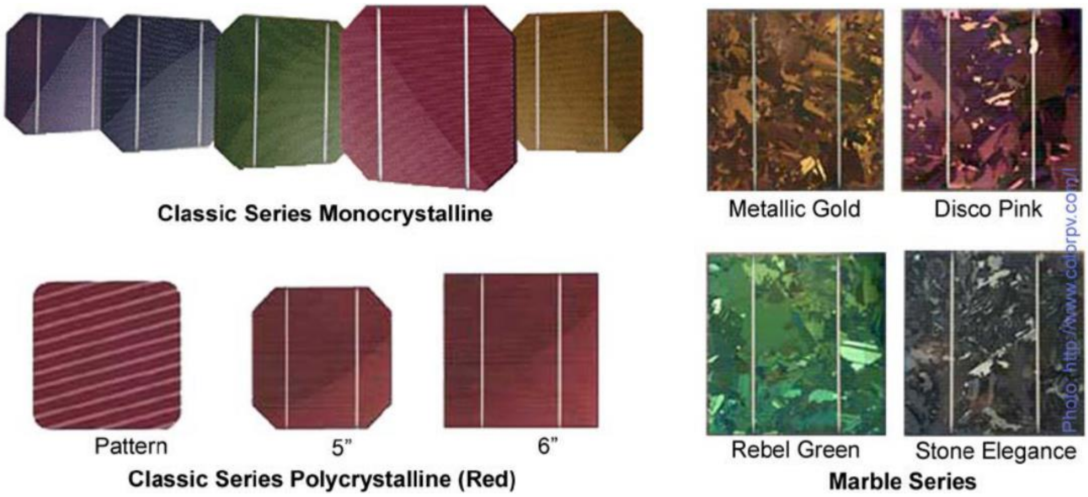


Figure 24. Range of colours in PV cells (Eder et al., 2019).

4.4 Texture and finish

Often, solar products such as PV cells and ST glazed collectors have glossy finishes to some extent. Sunlight reflects on them, causing the glare to be seen from considerable distances and even to be annoying in certain positions to those around them. For this reason, in the case of PV cells, for example, a structured glass cover is often used to give a matt finish (Roberts and Guariento, 2009).

An alternative to this type of finish is offered by unglazed ST collectors, which do not have a glazed plate and directly expose the surface of their absorber. As a result, they offer various options, from corrugated, embossed and perforated textures to matt, glossy and structured finishes (Kalogirou, 2015).

It is also related to the finish of the devices the level of transparency they have. Although mainly opaque products are commercialised, there is a growing number of translucent or semi-translucent options for both BIPV and BIST. Considering that there are more and more buildings with glazed facades, these options greatly expand the integration capacity of these devices.

5 Case study at Cranfield University

In order to put into practice the extensive literature review carried out so far, a brief proposal of potential solar energy BI opportunities at Cranfield University was made.

Once the buildings were chosen, the available surfaces were analysed and some proposals were made. To evaluate the potential production of these installations, *PVsyst* software was used. This is a very useful software for evaluating BI systems, as it takes into account parameters such as orientation, chosen technology, losses, storage and shading. However, it is focused only on PV devices, so all proposals were based on BIPV installations. Moreover, as the free version was used, the variety of PV modules available is rather limited. For this reason, the same c-Si module was used for every approach, although due to the characteristics of the different surfaces, other options such as thin-film PV would have been more appropriate. The module chosen is a generic monocrystalline device, consisting of 300 Wp and 60 cells.

The buildings chosen are some of the most representatives of the campus:

- King's Norton Library – Building 55
- Strategic Creativity Building – Building 82
- Vincent Building – Building 52a
- Whittle Building - Building 52
- Building 83
- AIRC – Building 320
- Martell House – Building 300

Some other options were also considered, such as the DARTeC building or the new Cranfield Air Park, which will include new hangars, a hotel and a biomass plant, among others (Central Bedfordshire Council, 2017). However, due to the lack of available information, it was decided not to include them.

The suggested installations are listed in Table_Apx 6, and thanks to the software it was calculated that they could generate around 1.3 TWh/year (see

Table_Apx 7). Bearing in mind that from the 2017/2018 academic year onwards the total consumption on campus has been around 17-20 TWh/year (see Figure 25), this production value would mean a saving of 6-8% of the total consumption of the university.

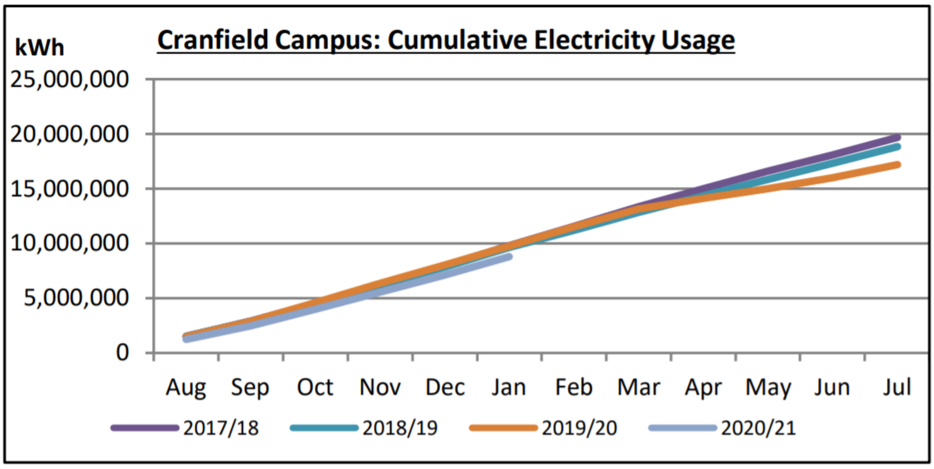


Figure 25. Cumulative electricity consumption in Cranfield University for the last four academic years (Cranfield University, 2020).

As can be seen in Table_Apx 7, the same comparison was also made for each of the buildings separately. For this purpose, the *SystemsLink* database was used (Cranfield University, 2021), which provides the electricity consumption of each building by year, together with other parameters. In some cases, higher outputs than the consumption of the building itself were achieved, as in the case of the AIRC Building or the C4D Building.

Assuming that the average UK electricity price in 2019 was 21.66 p/kWh (Statista Research Department, 2021), a total saving of around £292,000 was calculated. By estimating the price difference between BIPV devices and normal building materials, it could be concluded whether this proposal would be cost-effective and over what period of time.

Even if it was more expensive than a conventional refurbishment, the aesthetic enhancement and environmental benefit caused should be taken into account. As a matter of fact, it was estimated that the amount of metric tons of CO_2 not emitted into the atmosphere thanks to these installations would be 956.2 per year, assuming that on average for every MWh of electricity produced, 0.706

metric tons are emitted (United States Environmental Protection Agency (EPA), 2021).

6 Future development

In order to achieve a green energy transition as soon as possible and to exploit the enormous solar potential of buildings, there are several pathways to follow in the development and improvement of building-integrated solar devices. Here are a few of them.

6.1 Development of technologies and materials

To achieve better efficiencies at similar or lower prices, it is necessary to invest in the development of existing technologies and materials and research to find new ones.

The case of BIPV devices is particularly remarkable, for which several technologies have already been developed. While there is still a need to continue working on improving widely used PV cells such as c-Si and thin-film cells, future research will focus on the development of newer technologies. This includes cells such as dye-sensitised, quantum dot, perovskite, multi-junction and high-efficiency ones, among others.

While the efficiencies achieved in the case of BIST are already considerably high, the development of new and improved materials and technologies will focus on making them cheaper. To this end, not only the absorber but also the other components and processes involved will be taken into account.

The durability of these technologies will be an important consideration as well. A major effort will be devoted to finding and developing materials with longer utility life, in particular by making them more resistant to the external inclemencies that affect them.

6.2 Integrability improvement

Another of the objectives to be achieved in the short and medium term will be to considerably improve the integrability of the systems suggested and implemented to date. For this, it will be necessary to develop products that offer a much wider range in terms of sizes, shapes, colours, textures, flexibility, etc.

As has been repeatedly mentioned, BIPVs offer the greatest integrability to date, thanks to the wide range of product types they offer. However, it can get much higher if products with diverse qualities are commercialised to a greater extent.

In this integrability ranking, BISTs would be in second place. Even if their capacity to offer a wide variety of products is equal or even superior to that of the BIPV, what has been offered so far is still way behind.

In the case of hybrid systems, existing methods will have to be improved or new ways of combining PV and ST will have to be found, in order to make them more easily integrable. Something similar happens with concentrating systems, whose main problem is the integrability of the generally bulky and noticeable concentrators they use.

6.3 Investment and awareness-raising

In addition to improving materials and technologies and increasing their integrability, other key aspects to boost the market penetration of BI systems are as follows (Guillén et al., 2019):

- To raise awareness of BI solar technologies and their benefits.
- To promote the development of a more structural BI industry with highly skilled service providers, reducing uncertainty through standardisation of the sector and increased collaboration with the downstream value chain.
- To increase the energy renovation rate of buildings. For example, to achieve the EU's long-term climate and energy targets, the renovation rate should be increased from 1% to 3%. This would mean renovating 200 million buildings by 2050 (Renovate Europe, 2019).

To meet these objectives, especially the last two, public investment is not enough. Therefore, a public-private partnership in investment would be necessary, making use of mechanisms such as PPAs, EPCs or GPPs. In addition, it would also be necessary to help the private property owner to take part in this transformation through incentives, tax exemptions and loans (Guillén et al., 2019).

6.4 Search for innovative methods of urban solar farming

In addition to the promotion and research of what has already been achieved to develop and improve it, new ways of capturing the solar potential of urban centres will also have to be sought.

PV cells that work with unusual light

There are some ideas and prototypes of PV cells that do not work with the usual spectrum of sunlight. For example, researchers at Michigan State University have created a device that captures non-visible wavelengths such as ultraviolet and near-infrared but allows all visible sunlight to pass through (see Figure 26). If viable, it would be the first completely transparent PV cell (Mourant, 2014).

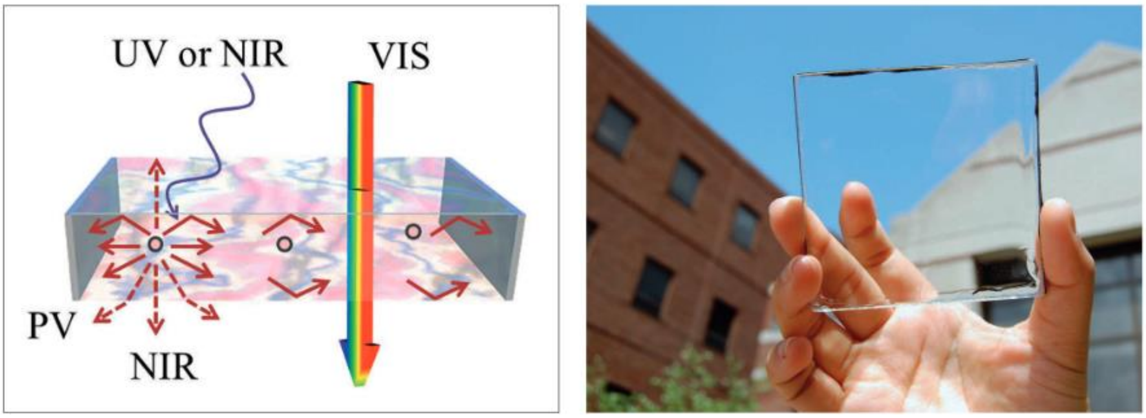


Figure 26. New PV cell prototype to harvest non-visible sun irradiance (Mourant, 2014).

Other researchers are trying to find a way to produce electricity from indoor artificial light. While there are PV cells capable of this, such as perovskite or dye-sensitised cells, their efficiencies are very low (Gallucci, 2020). In the meantime, an international research team has developed two “perovskiteinspired materials” capable of achieving efficiencies close to those of commercial cells (Hurley, 2020).

Solar integration in concrete

Given that concrete is ubiquitous in the urban environment, one capable of producing electricity would be a huge step forward. That is what they are working on at DysCrete by integrating organic dyes capable of absorbing solar radiation and generating electricity (Heike Klussman Studio Berlin, 2015).

Solar paint

Unlike what one might think, it is not a paint that is just added to any surface and generates electricity. It needs to be in contact with a conductive (electrode-coated) polymer or glass surface. This is what Javier and Foos (2009) achieved by using an airbrush to spray that surface with a solution of normal silver paint and CdSe and CdTe nanorods. Some other examples would be those developed from colloidal quantum dots (Moreno-Bautista, 2015) or perovskite (University of Sheffield, 2014). The efficiencies obtained are low, but this paves the way for the future integration of solar PV generation on almost any type of surface.

Integration in other urban surfaces

Other urban surfaces are also being considered for the integration of solar devices, e.g. pavements and roads. Other possibilities to consider include means of transport (ships, trains, aeroplanes, trucks, etc.), dams and reservoirs, windmills, etc (see Figure 27).

Figure 27. Examples of new integration surfaces: a) PV pavement in Barcelona, Spain (Otero, 2021); b) PV installation in Kotani Dam, Japan (Ioannis et al., 2014); c) PV system trial on a windmill in Spain (Richard, 2019)

7 Conclusion

As far as the structure of the report and the objectives set at the beginning are concerned, I consider that these guidelines have been followed considerably well. The main objective, which was the collection and presentation of all available information on Building-Integrated Solar Technologies, has been achieved. In addition, an attempt has been made to give a positive vision and to make readers aware of its enormous potential through the use of data, facts and real examples.

As far as the content of the report is concerned, it has been possible to create a very general overview of this branch of the solar energy sector. In conclusion, it has become clear that the potential of these technologies is enormous and that they could play a very important role in an energy transition that is becoming more and more urgent. This requires the involvement of both governments and the private sector in the research, development and marketing of the BI products and projects.

The BIPV branch is undoubtedly the most developed so far, mainly due to its low prices and general interest. However, if the aim is to one day develop cities with zero emissions, the investment will also have to focus on the other branches such as BIST, concentrating systems and hybrids. Especially since most residential and industrial consumption is in the form of heat. Many of the technologies needed to make BI installations viable already exist, all that is needed is to get people to develop cheaper and more suitable ways to make the integration functional but at the same time aesthetically pleasing.

Through the simple example of the case study at Cranfield University, it has become clear, once again, the enormous potential of building-integrated solar technologies. It is evident that the simulations and measurements carried out are far from accurate, and therefore the results obtained are probably considerably better than what would actually be achieved. However, in view of the results obtained, even if they were worse, they would still be very positive.

For the time being, due to their higher price (see Figure_Apx 2), the viability of these installations is still totally conditioned by their energy yield. However, as soon as their prices approach or even match those of the usual building materials, this will no longer be so relevant. Since even with much lower yields than expected, just for the energy, monetary and pollutant savings and for the aesthetic boost, it will be worth it.

REFERENCES

Adeeb, J., Farhan, A. and Al-Salaymeh, A. (2019) ‘Temperature effect on performance of different solar cell technologies’, *Journal of Ecological Engineering*, 20(5), pp. 249–254.

Al-Shohani, W.A.M., Al-Dadah, R., Mahmoud, S. and Algareu, A. (2016) ‘Optimum design of V-trough concentrator for photovoltaic applications’, *Solar Energy*, 140 Pergamon, pp. 241–254.

Arizton Advisory & Intelligence (2021) *Building Integrated Photovoltaics (BIPV) Market Size to Reach Revenues of USD 8.7 Billion by 2026 - Arizton*. Available at: https://www.prnewswire.com/news-releases/building-integrated-photovoltaics-bipv-market-size-to-reach-revenues-of-usd-8-7-billion-by-2026--arizton-301245621.html (Accessed: 21 July 2021).

Bavarian Association for the Promotion of Solar Energy (2020) *Architectural Award Building-Integrated Solar Technology 2020*. Available at: https://www.sev-bayern.de/2021/01/11/architectural-award-2020/ (Accessed: 9 July 2021).

Beck, M. (2020) *Why Europe and the US failed to capitalize on thin film solar*. Available at: https://www.pv-magazine.com/2020/01/10/why-europe-and-the-us-failed-to-capitalize-on-thin-film-solar/ (Accessed: 22 July 2021).

Becker, G., Haselhuhn, R., Hemmerle, C., Kämpfen, B., Krippner, R., Kuhn, T.E., Maurer, C., Reinberg, G.W. and Seltmann, T. (2017) *Building-Integrated Solar Technology: Architectural Design with Photovoltaics and Solar Thermal Energy*.

Bohg, A. and Briska, M. (2014) ‘Solar Energy Collectors’, *IBM Tech Disclosure Bull*, 19(7) Academic Press, pp. 125–220.

Boyd, L. (2010) *Picking a Base Absorber Material for Your Flat Plate Solar Collector*. Available at: https://www.doityourself.com/stry/picking-a-base-absorber-material-for-your-flat-plate-solar-collector (Accessed: 21 August 2021).

Burch, J. and Casey, R. (2009) ‘Wind issues in solar thermal performance ratings’, *38th ASES National Solar Conference 2009, SOLAR 2009*, 6(April), pp. 3577–3614.

Central Bedfordshire Council (2017) *Cranfield Air Park*. Available at: http://cbstor.centralbedfordshire.gov.uk/publicportalviewer/publicViewer.html?caseID=CB/17/05862/OUT (Accessed: 3 September 2021).

Chemisana, D. (2011) ‘Building Integrated Concentrating Photovoltaics: A review’, *Renewable and Sustainable Energy Reviews*, 15(1) Pergamon, pp. 603–611.

Chemisana, D. and Mallick, T.K. (2013) ‘Building integrated concentrating solar systems’, *Solar Energy Sciences and Engineering Applications*, (April 2015), pp. 503–524.

Conibeer, G. (2007) ‘Third-generation photovoltaics’, *Materials Today*, 10(11) Elsevier Ltd, pp. 42–50.

Cranfield University (2020) *Energy Champions and Reductions*. Available at: https://intranet.cranfield.ac.uk/EnergyEnvironment/Pages/Energy Champions and Reductions.aspx?Paged=TRUE&p_SortBehavior=0&p_FileLeafRef=Building B122 Electricity.pdf&p_ID=89&PageFirstRow=61&&View=%7B59F1F000-ACA3-4A8C-B63D-FEB315A592BB%7D (Accessed: 3 September 2021).

Cranfield University (2021) *SystemsLink*. Available at: https://cranfield.energymanagerlive.com/Group/GetGroupDetails/-1?selectTabName=Dashboards (Accessed: 3 September 2021).

Defaix, P.R., van Sark, W.G.J.H.M., Worrell, E. and de Visser, E. (2012) ‘Technical potential for photovoltaics on buildings in the EU-27’, *Solar Energy*, 86(9) Elsevier Ltd, pp. 2644–2653.

Eder, G., Peharz, G., Trattnig, R., Bonomo, P., Saretta, E., Frontini, F., Polo Lopez, C.S., Rose Wilson, H., Eisenlohr, J., Martín Chivelet, N., Karlsson, S., Jakica, N. and Zanelli, A. (2019) ‘*COLOURED BIPV Market, research and* *development IEA PVPS Task 15, Report IEA-PVPS T15-07: 2019*'

ESMAP (2020) '*Global Photovoltaic Power Potential by Country*', (June)

European Comission (2013) *Energy consumption by end-use*. Available at: https://ec.europa.eu/energy/content/energy-consumption-end-use_en (Accessed: 21 August 2021).

EUROSOLAR (n.d.) *European Solar Prize*. Available at: https://www.eurosolar.de/en/index.php/events/european-solar-prize-eurosolar (Accessed: 9 July 2021).

Fraunhofer Institute for Solar Energy Systems (2021) '*Photovoltaics Report*', (June)

Frontini, F., Bonomo, P., Chatzipanagi, A., Verberne, G., Donker, M. van den, Sinapis, K. and Folkerts, W. (2015) '*BIPV Product Overview for Solar Façades and Roofs*', , pp. 1–12.

Fuentes, M. (2007) 'Integration of PV into the built environment Guidelines', *Brita in PuBS*

Gajbert, H. (2008) *Solar thermal energy systems for building integration*.

Gallucci, M. (2020) *Next-Gen Solar Cells Can Harvest Indoor Lighting for IoT Devices*. Available at: https://spectrum.ieee.org/next-gen-solar-cells-harvest-indoor-lighting-iot-devices (Accessed: 3 September 2021).

Ghitas, A. (2012) 'Architectural Integration of Photovoltaic and Solar Thermal Collector Systems into Buildings for new Urban Planning', *The International Conference on Civil and Architecture Engineering*, 12(12), pp. 1–5.

Guillén, M.J., Schlatmann, R., Berlin, H.-Z., Sombsthay, A., Beauvais, A., Moser, D., Román, E., Gaymand, F., Delmer, G., Gurdenli, L., Machado, M., Po, R., Krawietz, S. and Karg, F. (2019) '*Solar Skins : An opportunity for greener cities*'

GVR (2020) *Europe Building-integrated Photovoltaics Market Size, Share & Trends Analysis Report By Technology (Crystalline Silicon, Thin Film), By*

Application (Roof, Façade, Glass), By End-use (Residential, Commercial, Industrial), And Segment Forecasts, 2020 - 2027. Available at: https://www.grandviewresearch.com/industry-analysis/europe-building-integrated-photovoltaics-market/segmentation (Accessed: 10 August 2021).

Heike Klussman Studio Berlin (2015) *DysCrete^{TM}*. Available at: http://www.klussmann.org/en/projects/DysCrete^{TM}?c=70 (Accessed: 3 September 2021).

Hermenean, I.S., Visa, I. and Diaconescu, D. V (2009) 'On the Geometric Modelling of a Concentrating Pv-Mirror System', *Bulletin of the Transilvania University of Brasov, Series I: Engineering Sciences*, 2(51), pp. 73–80.

Herzog, T. (1996) *Solar Energy in Architecture and Urban Planning. Solarenergie in Architektur und Stadtplanung*.

Honsberg, C. and Bowden, S. (n.d.) *Module Circuit Design | PVEducation*. Available at: https://www.pveducation.org/pvcdrom/modules-and-arrays/module-circuit-design (Accessed: 2 August 2021).

van den Hurk, L.B.P. and Teunissen, E.J.H.M. (2015) *Roadmap Building Integrated Photovoltaics. Bouwen aan BIPV*.

Hurley, B. (2020) *A Solar Alternative: How to Power Devices with Indoor Light*. Available at: https://www.techbriefs.com/component/content/article/tb/stories/blog/38116 (Accessed: 3 September 2021).

IEA (2020) '*Snapshot of Global PV Markets - 2020*'

Ioannis, K., Katalin, B., Arnulf, J.-W. and Sándor, S. (2014) 'Installing solar systems on the face of existing African dams for additional energy production', *Renewable Energies Unit, Institute for Energy and Transport, European Commission*, (September), pp. 1–34.

IRENA (2020) *Renewable Power Generation Costs in 2020*.

IRENA (2021) *Renewable Energy Capacity Statistics 2021*.

Javier, A. and Foos, E.E. (2009) ‘Nanocrystal photovoltaic paint sprayed with a handheld airbrush’, *IEEE Transactions on Nanotechnology*, 8(5), pp. 569–573.

Jelle, B.P. (2016) ‘Building integrated photovoltaics: A concise description of the current state of the art and possible research pathways’, *Energies*, 9(1), pp. 1–30.

Jeong, J. (2009) *PHOTOVOLTAICS: Measuring the ‘Sun’ | Laser Focus World*. Available at: https://www.laserfocusworld.com/lasers-sources/article/16566681/photovoltaics-measuring-the-sun (Accessed: 24 August 2021).

Jingchun Shen, X.Z., Luying Wang, Z.H., Llewellyn Tang, T.Y. and Yong Shi, Y.W. (2015) ‘Building Integrated Solar Thermal (BIST) Technologies and Their Applications: A Review of Structural Design and Architectural Integration’, *Journal of Fundamentals of Renewable Energy and Applications*, 05(05)

Kalogirou, S. (2015) ‘*COST Action TU1205 (BISTS) Building Integration of Solar Thermal Systems-BISTS Examples*’, 1205(July), pp. 1–9.

Keeping, S. (n.d.) *New PV Cells Benefit Energy Harvesting*. Available at: https://eu.mouser.com/applications/new-pv-cells-benefit-energy-harvesting/ (Accessed: 4 September 2021).

Kuchta, D.M. (2021) *History of Solar Energy: Timeline and Breakthroughs*. Available at: https://www.treehugger.com/history-of-solar-energy-timeline-and-breakthroughs-5183939 (Accessed: 9 July 2021).

Ladas, D.I., Stathopoulos, T. and Rounis, D. (2017) ‘*Wind effects on the performance of solar collectors on rectangular flat roofs: A wind tunnel study*’

Levy, B. (2017) *The First U.S. House to Go Solar | MIT Technology Review*. Available at: https://www.technologyreview.com/2017/04/25/152254/the-first-us-house-to-go-solar/ (Accessed: 8 July 2021).

Li, G., Xuan, Q., Akram, M.W., Golizadeh Akhlaghi, Y., Liu, H. and Shittu, S. (2020) ‘Building integrated solar concentrating systems: A review’, *Applied*

Energy, 260(December 2019) Elsevier, p. 114288.

Luque, A. and Viacheslav, A. (2007) *Inspira’s CPV Sun Tracking. Chapter 11: Concentrator Photovoltaics*.

Mallick, T.K. and Eames, P.C. (2007) ‘Design and fabrication of low concentrating second generation PRIDE concentrator’, *Solar Energy Materials and Solar Cells*, 91(7) North-Holland, pp. 597–608.

Maurer, C., Cappel, C. and Kuhn, T.E. (2017) ‘Progress in building-integrated solar thermal systems’, *Solar Energy*, 154 The Authors, pp. 158–186.

Maxeon US (n.d.) *Performance Solar Panels*. Available at: https://maxeon.com/us/solar-panel-products/performance-solar-panels (Accessed: 4 September 2021).

Meinardi, F., Bruni, F. and Brovelli, S. (2017) ‘Luminescent solar concentrators for building-integrated photovoltaics’, *Nature Reviews Materials*, 2 Macmillan Publishers Limited, pp. 1–9.

MIT Solar Decathlon Team (n.d.) *Solar1*. Available at: http://web.mit.edu/solardecathlon/solar1.html (Accessed: 5 September 2021).

Mofijur, M., Mahlia, T.M.I., Silitonga, A.S., Ong, H.C., Silakhori, M., Hasan, M.H., Putra, N. and Ashrafur Rahman, S.M. (2019) ‘Phase change materials (PCM) for solar energy usages and storage: An overview’, *Energies*, 12(16), pp. 1–20.

Moreno-Bautista, G. (2015) ‘*Efficient Spray-Coated Colloidal Quantum Dot Solar Cells by Efficient Spray-Coated Colloidal Quantum Dot Solar Cells*’

Mourant, A. (2014) ‘BIPV: Better form, improved function’, *Renewable Energy Focus*, 15(5) Elsevier Ltd, pp. 20–23.

Munari Probst, M.C. and Roecker, C. (2011) *Architectural Integration and Design of Solar Thermal Systems*.

Onyx Solar, R2M, Flisom, BEAR-iD and Acciona (2016) ‘*BIPV market and stakeholder analysis and needs Project report*’, (October 2016)

Orosz, M. and Dickes, R. (2017) ‘Solar thermal powered Organic Rankine Cycles’, *Organic Rankine Cycle (ORC) Power Systems: Technologies and Applications*, Woodhead Publishing, pp. 569–612.

Osseweijer, F.J.W., van den Hurk, L.B.P., Teunissen, E.J.H.M. and van Sark, W.G.J.H.M. (2018) ‘A comparative review of building integrated photovoltaics ecosystems in selected European countries’, *Renewable and Sustainable Energy Reviews*, 90(April 2017) Elsevier Ltd, pp. 1027–1040.

Otero, C. (2021) *Las calles del futuro en Barcelona: Aceras solares para generar energía renovable*. Available at: https://as.com/meristation/2021/05/03/betech/1620064505_681737.html (Accessed: 3 September 2021).

Purcell-Milton, F. and Gun’ko, Y.K. (2012) ‘Quantum dots for Luminescent Solar Concentrators’, *Journal of Materials Chemistry*, 22(33), pp. 16687–16697.

PVEasy (2017) *Shading and how to mitigate it*. Available at: https://www.pveasy.com.au/blog/2017/7/shading-and-how-to-mitigate-it (Accessed: 4 September 2021).

Rathore, N., Panwar, N.L., Yettou, F. and Gama, A. (2019) ‘A comprehensive review of different types of solar photovoltaic cells and their applications’, *International Journal of Ambient Energy*, Taylor & Francis, pp. 1–18.

Renovate Europe (2019) *About the Campaign – Renovate Europe*. Available at: https://www.renovate-europe.eu/about-the-campaign/ (Accessed: 3 September 2021).

Richard, C. (2019) *Acciona trials solar modules to power wind turbine*. Available at: https://www.windpowermonthly.com/article/1584900/acciona-trials-solar-modules-power-wind-turbine (Accessed: 3 September 2021).

Roberts, S. and Guariento, N. (2009) ‘*Building Integrated Photovoltaics: A Handbook*’, , pp. 68–70.

Rühle, S. (2016) ‘Tabulated values of the Shockley-Queisser limit for single junction solar cells’, *Solar Energy*, 130, pp. 139–147.

Sandhu, J. (2021) *Best Solar Panel Angle: How Do You Find It — And Does it Matter?*. Available at: https://www.solarreviews.com/blog/best-solar-panel-angle (Accessed: 23 July 2021).

Seltman, W. (2020) *Eyeglasses: Lens Types, Lens Coatings, Bifocals, and Trifocals*. Available at: https://www.webmd.com/eye-health/eyeglasses-eyes (Accessed: 26 August 2021).

Simya, O.K., Radhakrishnan, P., Ashok, A., Kavitha, K. and Althaf, R. (2018) ‘Engineered Nanomaterials for Energy Applications’, *Handbook of Nanomaterials for Industrial Applications*, Elsevier, pp. 751–767.

Statista Research Department (2021) *Electricity prices for households in the United Kingdom (UK) from 2010 to 2020, semi-annually*. Available at: https://www.statista.com/statistics/418126/electricity-prices-for-households-in-the-uk/ (Accessed: 4 September 2021).

Szabó, L. (2017) ‘The history of using solar energy’, *The History of Using Solar Energy*, (June 2017)

Tindo Solar (n.d.) *Poly vs Mono Crystalline*. Available at: https://www.tindosolar.com.au/learn-more/poly-vs-mono-crystalline/ (Accessed: 21 July 2021).

Tiwari, R. (2016) *2020 CPV Market (Concentrated Photovoltaic) Size, Country Analysis and Forecasts*. Available at: https://www.prnewswire.com/in/news-releases/2020-cpv-market-concentrated-photovoltaic-size-country-analysis-and-forecasts-576702721.html (Accessed: 23 August 2021).

Tripanagnostopoulos, Y. (2014) ‘New designs of building integrated solar energy systems’, *Energy Procedia*, 57 Elsevier B.V., pp. 2186–2194.

Tripanagnostopoulos, Y., Souliotis, M. and Nousia, T. (2000) ‘Solar collectors with colored absorbers’, *Solar Energy*, 68(4) Pergamon, pp. 343–356.

U.S. Energy Information Administration (EIA) (2015) *Space heating and water* *heating account for nearly two thirds of U.S. home energy use*. Available at: https://www.eia.gov/todayinenergy/detail.php?id=37433 (Accessed: 21 August 2021).

UNEP (2014) '*Integrating Solar Thermal in Buildings – A quick guide for Architects and Builders*'

United States Environmental Protection Agency (EPA) (2021) *Greenhouse Gas Equivalencies Calculator*. Available at: https://www.epa.gov/energy/greenhouse-gas-equivalencies-calculator (Accessed: 4 September 2021).

University of Sheffield (2014) *Scientists develop pioneering new spray-on solar cells - Archive - News archive - The University of Sheffield*. Available at: https://www.sheffield.ac.uk/news/nr/spray-on-solar-cells-1.392919 (Accessed: 3 September 2021).

Ürge-Vorsatz, D., Cabeza, L.F., Serrano, S., Barreneche, C. and Petrichenko, K. (2014) 'Heating and cooling energy trends and drivers in buildings', *Renewable and Sustainable Energy Reviews*, 41 Elsevier, pp. 85–98.

US Department of Energy (n.d.) *Solar Decathlon*.

Vega Sánchez, S. (2011) '*Solar Decathlon Europe 2010*', 107(1), pp. 66–77.

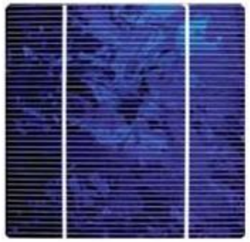
Vidyanandan, K. (2017) 'An Overview of Factors Affecting the Performance of Solar PV Systems', *Energy Scan*, 27(February), pp. 2–8.

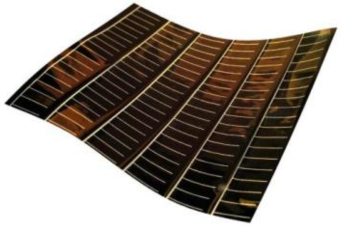
APPENDICES

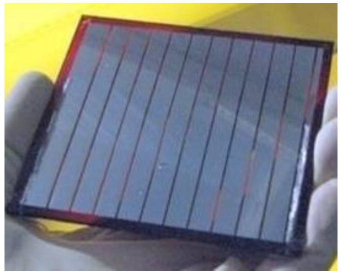
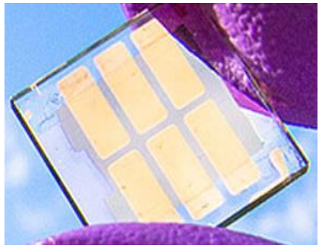
Appendix A Supplementary information for Chapter ¡Error! No se encuentra el origen de la referencia.: State of the Art

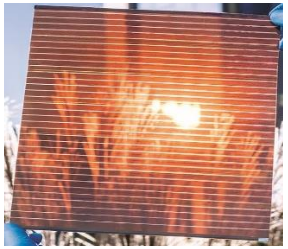
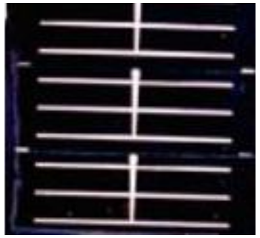
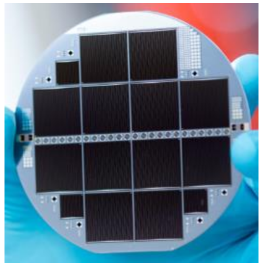
A.1 Additional information about BIPV

Table_Apx 1. PV cells used in BIPV and their characteristics.

Type of PV cell		Picture	Best cell efficiency in laboratory (%)	Additional details
First-generation cells (c-Si)	Monocrystalline		26.7 [1]	Homogeneous appearance, typically with black, grey or blue colour. Common shapes are square, round and semi-round. Usually, an anti-reflection coating is added to increase the amount of absorbed light. Highest efficiency, market share and price among c-Si. [3]
	Polycrystalline		24.4 [1]	Heterogeneous appearance with multiple shades, typically with medium or dark blue colours. [3]

Second-generation cells (thin film)	Amorphous silicon (a-Si)		14 [2]	Typical thicknesses are around one µm or even a few nm, so they are lighter. These thin layers are usually deposited on glass, metal or plastic substrates. Lower material and energy consumption in the production phase, and therefore, lower prices. Completely homogeneous appearance, usually with dark colours. They are flexible and they have adaptable shapes and sizes. [3] At the moment, research is focused on CIS/CIGS and CdTe. The highest market share corresponds to CdTe, followed by CIS/CIGS. [1]
	CIS/CIGS		23.4 [2]	
	CdTe		22.1 [2]	
	GaAs		29.1 [2]	Highest efficiency among single-junction cells, thanks to its III-V direct bandgap semiconductor material. Benefits over other commercial technologies: higher electron mobility, relatively insensitive to overheating, wider bandgap, etc. High cost, many applications in the aerospace industry. [4]

Third-generation cells (emerging PV)	Dye-sensitized		13 [2]	They also belong to the thin-film category. They have been under research for more than two decades due to their features: low cost, easy production and low toxicity. The efficiencies achieved so far, however, are not good enough to compete with the first and second-generation. [5]
	Organic		18.2 [2]	Benefits over inorganic materials: low cost, lightweight, strong, flexibility and tunable absorptivity. Disadvantage: photochemical degradation. [6]
	Quantum dot (nanocrystal based)		18.1 [2]	It uses quantum dots as the absorbing material. Its size can get very small, which benefits it in comparison to others such as c-Si. The bandgaps of the dots can be tuned by changing their size. Therefore, it is possible to increase production by doing that. [7]

	Perovskite		25.5 [2]	This is the most recent emerging technology. Probably the most rapid growth in efficiencies among all of them. It’s also a thin-film technology, and it has already surpassed the highest efficiency of the most commercialised mainstream thin-film technology (CdTe). [6]
	CZTS		12.6 [2]	They emerged as substitutes for CIS/CIGS and CdTe, mainly because, unlike them, their constituent materials (copper zinc tin sulphide) are abundant and non-toxic. [8]
Others	Multi-junction		39.2 [2]	Unlike all of the above (single-junction cells), these cells have more than one p-n junction or bandgap with different semiconductor materials. In this way, they can collect a wider spectrum of sunlight. [9] Highest recorded cell efficiency so far. If combined with a concentrator, efficiencies of up to 47.1% have been recorded. [2]
	Bifacial		-	These cells are capable of absorbing irradiance from both sides. In some cases, such as concentrating systems, they can be very useful. Their efficiency will depend on the technology they use on each side, but it has been estimated that they can increase it by 11% compared to the monofacial ones with the same technologies. [10]

References from Table_Apx 1

[1] Fraunhofer Institute for Solar Energy Systems (2021) ‘*Photovoltaics Report*’, (June)

[2] NREL (2020) *Best Research-Cell Efficiencies*.

[3] Roberts, S. and Guariento, N. (2009) ‘*Building Integrated Photovoltaics: A Handbook*’, , pp. 68–70.

[4] De Rooij, D. (n.d.) *GaAs Solar Cells*. Available at: https://sinovoltaics.com/learning-center/solar-cells/gaas-solar-cells/ (Accessed: 4 September 2021).

[5] Sharma, K., Sharma, V., & Sharma, S. S. (n.d.). Dye-Sensitized Solar Cells: Fundamentals and Current Status. https://doi.org/10.1186/s11671-018-2760-6

[6] Ben Dkhil, S. (n.d.) *What is the “third generation” of photovoltaic?* Available at: https://dracula-technologies.com/what-is-the-third-generation-of-photovoltaic/ (Accessed: 4 September 2021).

[7] Report, T. (2016) ‘*Characterization and Analysis of Quantum-Dot PV Solar-Cells*’, (January)

[8] McClary, S. (2016) *CZTSSe*. Available at: https://www.pveducation.org/es/fotovoltaica/czts (Accessed: 4 September 2021).

[9] Office of Energy Efficiency and Renewable Energy (n.d.) *Multijunction III-V Photovoltaics Research*. Available at: https://www.energy.gov/eere/solar/multijunction-iii-v-photovoltaics-research (Accessed: 4 September 2021).

[10] McCalmont, K. (2020) *How Bifacial Solar Panels Can Significantly Increase Your Energy Efficiency*. Available at: https://goenergylink.com/blog/bifacial-solar-increases-energy-efficiency/ (Accessed: 4 September 2021).

Table_Apx 2. Some examples of real BIPV installations with different types of PV products and technologies.

Product type	Installation location	Building surface	Product name	Installation picture	Company, Country	PV Technology	Reference
BIPV Tiles	Strand Church, Trau, Norway	Pitched roof	Solar Roof	(1)	SunStyle, Switzerland	Monocrystalline	[1]
	Sweden	Pitched roof	Hantile	(2)	Hanergy, The Netherlands	Thin-film	[2]
	Dallas, Texas, USA	Pitched roof	Solar Roof	(3)	Tesla, USA	Monocrystalline	[3]
	Huizen, The Netherlands	Pitched roof	X-Roof	(4)	Exasun, The Netherlands	Monocrystalline	[4]
	-	Pitched roof	Solar Shingle	(5)	Luma Solar	Monocrystalline	[5]
BIPV Modules	Münsingen, Germany	Vertical façade	MegaSlate II	(6)	Solar Plus, Switzerland	Monocrystalline	[6]
	Ørestad Gymnasium, Copenhagen, Denmark	Vertical sunshades	Shadovoltaic	(7)	Colt, UK	Monocrystalline/ Polycrystalline	[7]
	Basel, Switzerland	Vertical façade and pitched roof	Kromatix™	(8)	Swissinso, Switzerland	Monocrystalline/Polycrystalline	[8]
	Marcegaglia Headquarters, Mantova, Italy	Pitched roof	Brollo Solar	(9)	Marcegaglia, Italy	Thin-film	[9]

	Solaxess SA, Switzerland	Vertical façcade	Custom made product	(10)	Solaxess, Switzerland	Thin-film	[10]
BIPV Foil	Coca Cola Enterprise, Los Angeles, USA	Horizontal (almost) roof	PowerBond	(11)	Unisolar, USA	Thin-film	[11]
	Vigonovo di Fontanafredda, Italy	Curved-horizontal roof	-	(12)	FlexCell	Thin-film	[9]
	Glafey candle factory, Nuremberg, Germany	Flat roof	EVALON® Solar cSi	(13)	Alwitra, Germany	c-SI	[12]
	Schiller School, Bretten, Germany	Curved roof	AluPlusSolar	(14)	Kalzip	Thin film	[13]
	Niederhasli, Switzerland	Curved and flat roof	eFlex	(15)	Flisom, Switzerland	Thin film (CIGS)	[14]
BIPV Cell-glazing	-	Balcony	MegaSlate	(16)	Solar Plus, Switzerland	Monocrystalline	[15]
	Kazakh Pavilion, Expo2017, Astana, Kazakhstan	Curved façade/roof	Custom made product	(17)	Ertex Solar, Austria	Monocrystalline	[16]
	Bejar Market, Salamanca, Spain	Skylight (saw-toothed roof)	Custom made product	(18)	Onyx Sola, Spainr	Thin-film (a-Si)	[17]
	SwissTech Convention Center, EPFL, Switzerland	Vertical curtain wall	Custom made product	(19)	Solaronix, Switzerland	Dye-sensitized	[18]
	Bergopwaarts headquarters, The Netherlands	Verical sunshades	Shadoglass	(20)	Colt, UK	Monocrystalline/Polycrystalline	[7]

References from Table_Apx 2

[1] SunStyle (n.d.) *The future of solar roofing*. Available at: https://www.sunstyle.com/ (Accessed: 6 September 2021).

[2] Hantile (n.d.) *Hantile solar roof tiles: thin film power to the max*. Available at: https://www.hanergy.eu/hantile-solar-roof-tiles/ (Accessed: 6 September 2021).

[3] Tesla (n.d.) *Solar Roof*. Available at: https://www.tesla.com/es_es/solarroof (Accessed: 6 September 2021).

[4] Exasun (n.d.) *X-Roof*. Available at: https://exasun.com/en/bestellen/zonnepanelen-en/x-roof/ (Accessed: 6 September 2021).

[5] LUMA Solar (n.d.) *Solar Roof: Shingle Specifications*. Available at: https://lumasolar.com/solar-roof/ (Accessed: 6 September 2021).

[6] Solar Plus (n.d.) *MegaSlate II | Il Modulo Solare Integrato Svizzero*. Available at: https://3s-solarplus.ch/it/megaslate_ii_it/ (Accessed: 6 September 2021).

[7] Colt (n.d.) *Shadovoltaic photovoltaic solar shading*. Available at: https://www.coltinfo.co.uk/colt-product-library/solar-shading/photovoltaic-shading-pv-shading-louvre/specification.html (Accessed: 6 September 2021).

[8] SwissINSO (n.d.) *COAL SILO REDEVELOPMENT*. Available at: https://www.swissinso.com/kohlensilo (Accessed: 6 September 2021).

[9] LESO-PB (n.d.) *Innovative solar products for building integration*. Available at: https://www.solarintegrationsolutions.org/index.php?page=home (Accessed: 6 September 2021).

[10] SOLAXESS (n.d.) *The company and its products*. Available at: https://www.solaxess.ch/en/the-company-its-product/ (Accessed: 6 September 2021).

[11] Uni-Solar (n.d.) *Coca Cola*. Available at: http://www.uni-solar.com/real-stories-2/coca-cola/index.html (Accessed: 6 September 2021).

[12] Alwitra (n.d.) *Glafey candle manufactory, Nuremberg*. Available at: https://alwitra.de/en/referenz/glafey-candle-manufactory-nuremberg-germany/ (Accessed: 6 September 2021).

[13] Kalzip® Solar Systems (n.d.) *Roof Systems*. Available at: https://www.kalzip.com/en/products/kalzip-roof-systems/kalzip-solar-systems/#toggle-id-4 (Accessed: 6 September 2021).

[14] Flisom (n.d.) *eFlex – lightweight flexible solar panels*. Available at: https://www.flisom.com/products/ (Accessed: 6 September 2021).

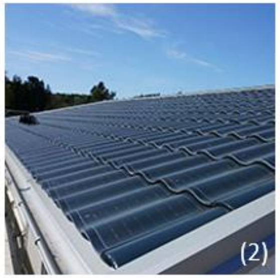
[15] Solar Plus (n.d.) *MegaSlate Parapetto solare | 3S Solar Plus AG*. Available at: https://3s-solarplus.ch/it/megaslate-parapetto-solare/ (Accessed: 6 September 2021).

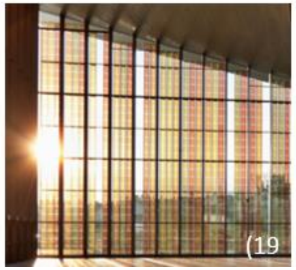
[16] Ertex Solar (n.d.) *Semi-transparent Modules - ertex solar - Individuell gefertigte Photovoltaik-Module zur kreativen Gebäudeintegration*. Available at: https://www.ertex-solar.at/en/products/semi-transparent-modules/ (Accessed: 6 September 2021).

[17] Onyx Solar (n.d.) *Bejar Market Spain*. Available at: https://www.onyxsolar.com/bejar-market (Accessed: 6 September 2021).

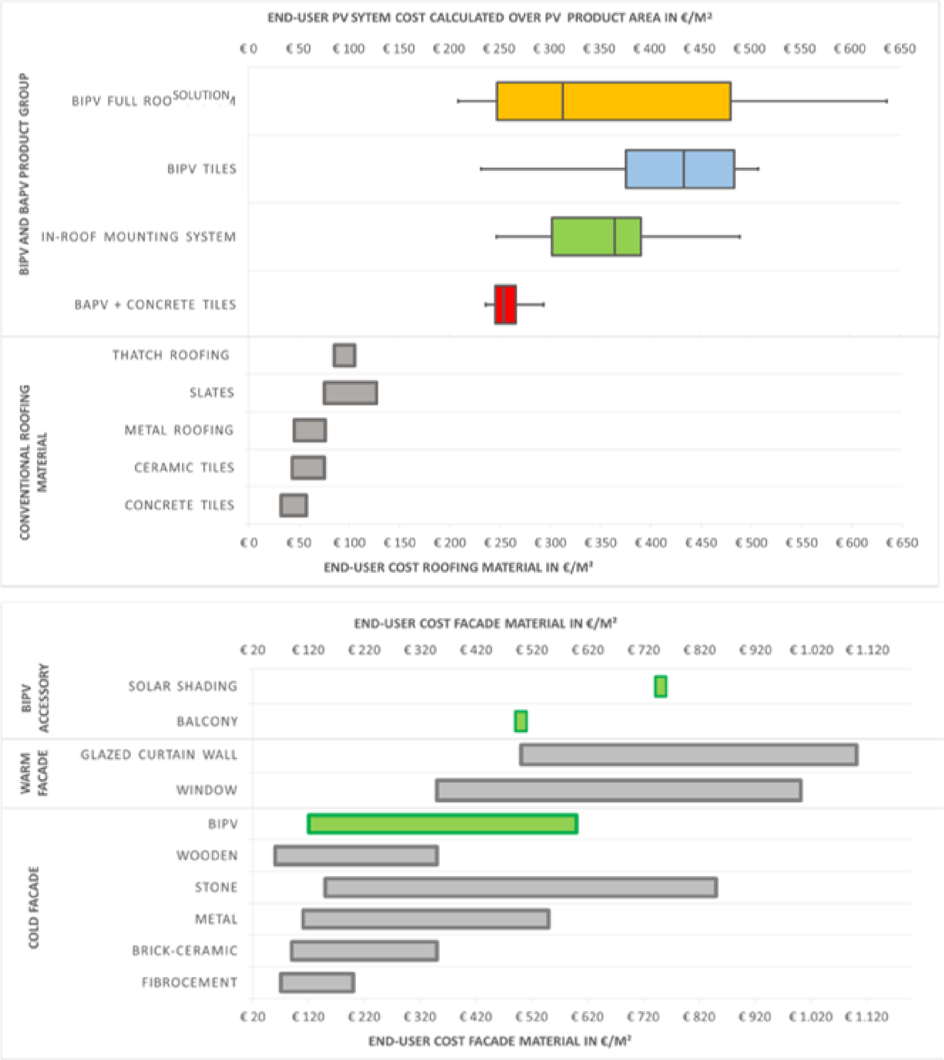
[18] Solaronix (n.d.) *Solar Cells*. Available at: https://www.solaronix.com/solarcells/ (Accessed: 6 September 2021).

Figure_Apx 1. Pictures of the installations gathered in Table_Apx 2





Figure_Apx 2. Cost comparison between BIPV and standard building materials in roof and façades.



A.2 Additional information about BIST

Table_Apx 3. Some examples of real BIST installations with different types of ST products and technologies.

ST technology type	Product type	Installation picture	Installation location	Building surface	Employed fluid	Application	Product name	Company, Country	Reference
Flat-plate collector	Modular, opaque	(1)	Nenzing, Austria	Vertical façade	-	-	-	Domasolar, Austria	[1]
	Modular, semi-transparent	(2)	Paris, France	Vertical façade	Water	DHW		Robin Sun, France	[2]
	Modular, opaque	(3)	Passive house Rudshagen, Oslo, Norway	Vertical façade	Water	DHW, space heating	AventaSolar	Aventa AS	[3]
	Cover, opaque	(4)	Flagstaff, Northern Arizona University, USA	Vertical façade	Air	Space heating	-	SolarWall	[4]
Unglazed collector	Flat tiles, opaque	(5)	Wetzlar, Germany	Pitched roof	Water	DHW	QUICK STEP Solar Thermie	Rheinzink, Germany	[5]
	Modular, opaque	(6)	Chancy, France	Pitched roof	Water	DHW	AS	Energie Solair, France	[6]
	Tiles, opaque	(7)	Eden Clinic, Switzerland	Pitched roof	Water	DHW, space heating,	Custom made	Atmova	[7]

						swimming pool heating			
	Modular, opaque	(8)	The centre d'exploitation des Routes Nationales (CeRN), Bursins, Switzerland	Vertical façade	Water	DHW, floor heating	AS	Energie Solair, France	[5]
Evacuated-tube collector	Translucent	(9)	Sunny Woods, Zurich, Switzerland	Balcony railings	Water	DHW, space heating	-	-	[8]
	Translucent	(10)	Amden, Switzerland	Balcony railings	Water	DHW, space heating	Custom made	Schweizer Energie, Switzerland	[9]
	Curved tile	(11)	-	Pitched roof	Water	DHW, space heating	Techtile Therm	REM	[10]
	Translucent	(12)	-	Curtain wall	-	Space heating and cooling	Prototype	University of Stuttgart	[11]

References from Table_Apx 3

[1] DOMA Solartechnik (n.d.) *Photovoltaik und Solaranlagen aus Vorarlberg*. Available at: https://www.domasolar.com/ (Accessed: 6 September 2021).

[2] Jingchun Shen, X.Z., Luying Wang, Z.H., Llewellyn Tang, T.Y. and Yong Shi, Y.W. (2015) 'Building Integrated Solar Thermal (BIST) Technologies and Their Applications: A Review of Structural Design and Architectural Integration', *Journal of Fundamentals of Renewable Energy and Applications*, 05(05)

[3] Aventa AS (n.d.) '*Passive house Rudshagen, Oslo, Norway Architectural integration of solar thermal energy systems*'

[4] SolarWall (n.d.) *Northern Arizona University – LEED Silver*. Available at: https://www.solarwall.com/case-study/northern-arizona-university/ (Accessed: 6 September 2021).

[5] Rheinzink (n.d.) *RHEINZINK – the world's no. 1 in titanium zinc*. Available at: https://www.rheinzink.com/ (Accessed: 6 September 2021).

[6] Energie Solaire SA (n.d.) *Accueil*. Available at: https://www.energie-solaire.com/ (Accessed: 6 September 2021). Energie Solaire SA (n.d.) *Amélioration énergétique et surélévation Minergie® d'un immeuble de logement locatif*. Available at: https://www.energie-solaire.com/wq_pages/fr/site/page-299.php (Accessed: 6 September 2021).

[7] ATMOVA (n.d.) *Neue Energie für gute Erholung*. Available at: http://www.atmova.com/de/inhalt/referenzen/kurklinik-eden.html (Accessed: 6 September 2021).

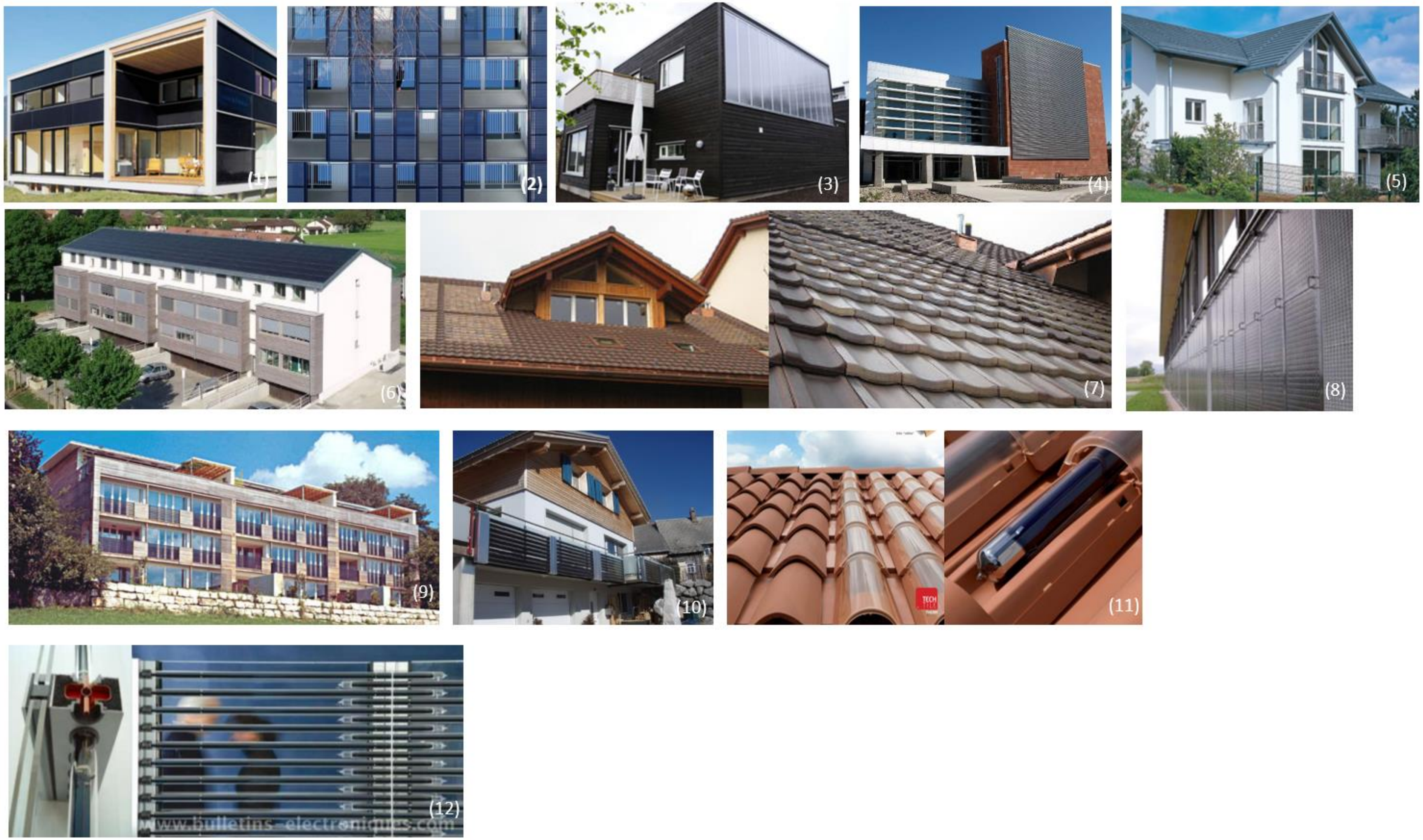
[8] IEA SHC (n.d.) '*Sunny Woods*'

[9] Schweizer-Energie (n.d.) *EFH Amden (SG)*. Available at: http://www.schweizer-energie.ch/reference/efh-amden-sg (Accessed: 6 September 2021).

[10] REM (2011) '*Techtile Therm: Impianti solari termici integrati*'

[11] LESO-PB (n.d.) *Innovative solar products for building integration*. Available at: https://www.solarintegrationsolutions.org/index.php?page=home (Accessed: 6 September 2021).

Figure_Apx 3. Pictures of the installations gathered in Table_Apx 3.



A.3 Additional information about BICS

Table_Apx 4. Some examples of BICS products, prototypes and designs with different types of CS products and technologies.

Concentrator type	Installation Picture	Building surface	Design/prototype/ commercialised?	BICPV or BICST?	Reference
Flat reflector	(1)	Saw-toothed roof	Design	BIC Hybrid	[1]
Parabolic trough (with tracking system)	(2)		Prototype	BICST	[2]
CPC	(3)	-	Design	BICST	[3]
	(4)	-	Prototype	BICPV	[4]
	(5)	Vertical façade	Prototype	BICPV	[5]
	(6)	Horizontal roof	Design	-	[6]
	(7)	Horizontal roof (with glazed plate)	Design	-	[7]
	(8)	Horizontal, saw-toothed	Design	-	[7]
	(9)	Pitched roof	Design	-	[7]
	(10)	Flat roof	Design	BICST	[7]
	(11)	Vertical façade	Design	-	[7]

	(12)	Vertical façade, sunshade	Design	-	[6]
	(13)	Under balconies	Design	-	[6]
	(14)	Curtain wall, translucent	Design	BIC Hybrid	[8]
	(15)	Curved façade and pitched façade	Design	BICST	[9]
	(16)	Flat roof, kind of saw-toothed	Design	BICST	[9]
Fresnel lens	(17)	Curtain wall, translucent	Design	BICPV	[10]
	(18)	Skylight/atrium	Design	BICST or BIC Hybrid	[9]
	(19)	Curtain wall, translucent	Commercialised, Lumiduct (with tracking system)	BICPV, but also BIC Hybrid possible	[11]
Fresnel mirror	(20)	Vertical façade, sunshade	Prototype	BICPV	[12]
	(21)	Roof	Prototype	-	[8]
	(22)	Flat roof and tower	Design	-	[7]
LSC	(23)	Curtain wall and skylight, translucent	Commercialised product, ENERGYGLASS™	BICPV	[13]

References from Table_Apx 4

[1] REM (2011) Abdul Hamid, S., Yusof Othman, M., Sopian, K. and Zaidi, S.H. (2014) 'An overview of photovoltaic thermal combination (PV/T combi) technology', *Renewable and Sustainable Energy Reviews*, 38 Elsevier, pp. 212–222.

[2] Yang, M., Moghimi, M.A., Zhu, Y., Qiao, R., Wang, Y. and Taylor, R.A. (2020) 'Optical and thermal performance analysis of a micro parabolic trough collector for building integration', *Applied Energy*, 260 Elsevier, p. 114234.

[3] Xu, R.J., Zhang, X.H., Wang, R.X., Xu, S.H. and Wang, H.S. (2017) 'Experimental investigation of a solar collector integrated with a pulsating heat pipe and a compound parabolic concentrator', *Energy Conversion and Management*, 148, pp. 68–77.

[4] Feng, C., Zheng, H., Wang, R., Yu, X. and Su, Y. (2015) 'A novel solar multifunctional PV/T/D system for green building roofs', *Energy Conversion and Management*, 93, pp. 63–71.

[5] Brogren, M., Wennerberg, J., Kapper, R. and Karlsson, B. (2003) 'Design of concentrating elements with CIS thin-film solar cells for façade integration', *Solar Energy Materials and Solar Cells*, 75(3–4), pp. 567–575.

[6] Kalogirou, S.A. (2015) 'Building integration of solar renewable energy systems towards zero or nearly zero energy buildings', *International Journal of Low-Carbon Technologies*, 10(4), pp. 379–385.

[7] Goodman, J.H. (2010) 'Building integrated CSP selected studies', *39th ASES National Solar Conference 2010, SOLAR 2010*, 2(August), pp. 1265–1274.

[8] Li, G., Xuan, Q., Akram, M.W., Golizadeh Akhlaghi, Y., Liu, H. and Shittu, S. (2020) 'Building integrated solar concentrating systems: A review', *Applied Energy*, 260(December 2019) Elsevier, p. 114288.

[9] Tripanagnostopoulos, Y. (2014) 'New designs of building integrated solar energy systems', *Energy Procedia*, 57 Elsevier B.V., pp. 2186–2194.

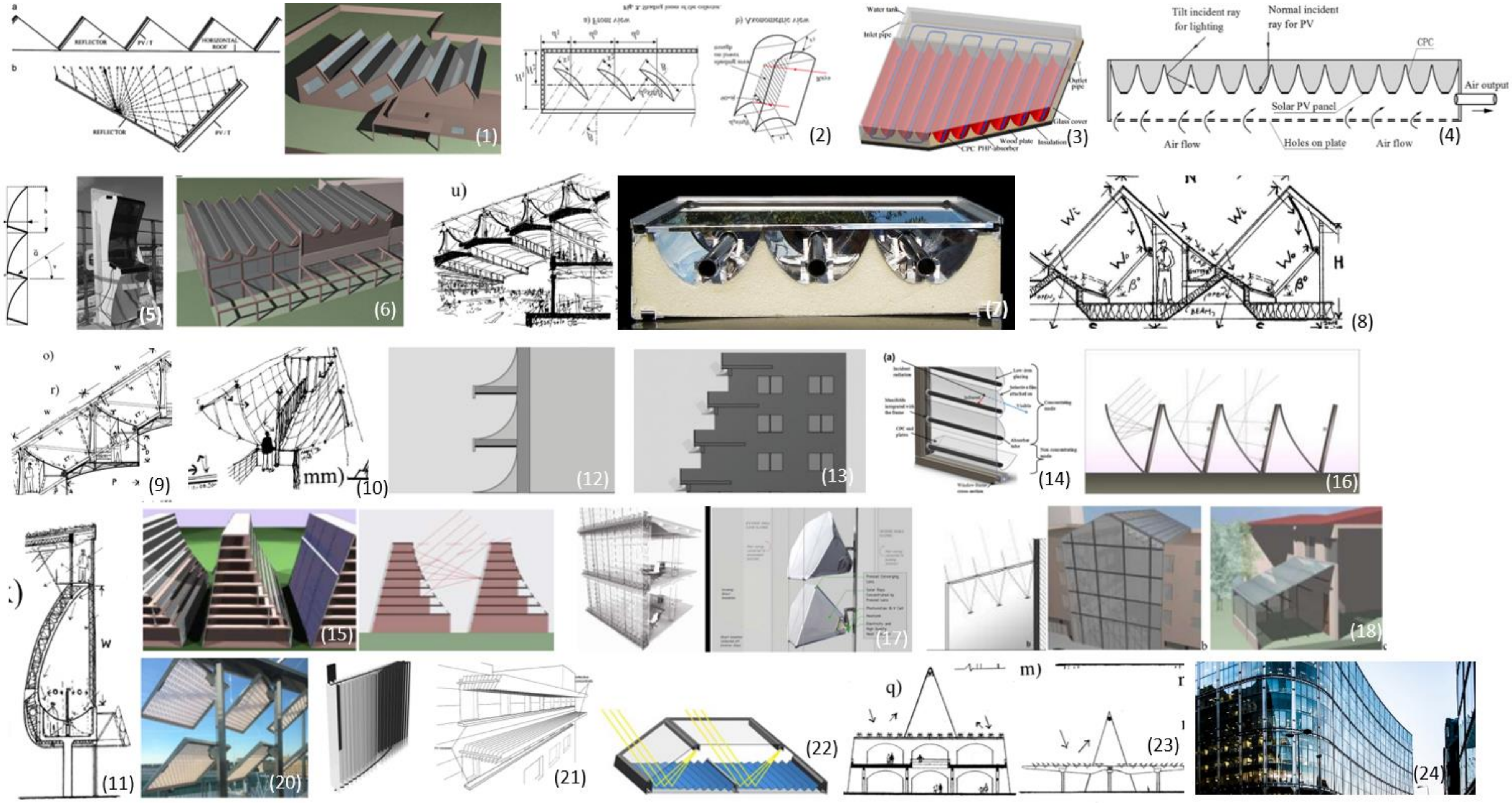
[10] Dyson, A.H., Stark, P.R. and Jensen, M.K. (2009) '*Integrated Concentrating (IC) Solar Façade System*', (Ic), pp. 2–3.

[11] Wellsun (n.d.) *Lumiduct*. Available at: https://www.wellsun.nl/lumiduct (Accessed: 6 September 2021).

[12] Chemisana, D. and Rosell, J.I. (2011) ‘Design and optical performance of a nonimaging Fresnel transmissive concentrator for building integration applications’, *Energy Conversion and Management*, 52(10) Elsevier Ltd, pp. 3241–3248.

[13] Energy Glass (n.d.) *About EnergyGlass — What is Energy Glass?*. Available at: http://energyglass.com/egl/about-us.php (Accessed: 6 September 2021).

Figure_Apx 4. Pictures of the installations gathered in Table_Apx 4.



A.4 Additional information about Hybrid Systems (BIPVT)

Table_Apx 5. Some examples of Hybrid installations with different types of BIPVT products and technologies.

Working principle	PV/T Technologies	Installation location	Building surface	Product name	Installation picture	Company, Country	Reference
Air-cooled	-	John Molson School of Business, Concordia University, Montreal, Canada	Vertical façade	PV/T	(1)	SolarWall	[1]
	-	Beijing Olympic Village, China	Curved façade	PV/T	(2)	SolarWall	[2]
	-	-	Pitched roof	Indach	(3)	Solator	[3]
	Polycrystalline silicon and a ventilated chamber	Pompeu Fabra Library, Spain	Ventilated double-skin façade	Custom made	(4)	ASE, TFM (Teulades i Façanes Multifuncionals)	[4]
	Polycrystalline silicon PV	Lisbon, Portugal	Vertical façade	Prototype	(5)	-	[5]
Water-cooled	Hybrid absorber with CPC concentrator	Solgarden, Sweden	Window	Prototype	(6)	-	[5]

	Monocrystalline silicon and copper ST absorber	Campagna Lupia (VE), Italy	Curtain wall, translucent	Cs Series	(7)	FotoTherm	[6]
	Monocrystalline silicon PV	Pearl Beach, New South Wales, Australia	Pitched roof	Solar Roof Tile	(8)	Tractile	[7]
	-	-	Balcony	Solar Balcony	(9)	FotoTherm	[8]

References from Table_Apx 5

[1] SolarWall (n.d.) *John Molson School of Business at Concordia University*. Available at: https://www.solarwall.com/case-study/concordia-university/ (Accessed: 6 September 2021).

[2] Asia Business Council (2008) ‘*Beijing Olympic Village*’, , p. 14226.

[3] Solator (n.d.) *Solator - use the sun twice: solator INDACH*. Available at: http://www.solator.cc/system/solator-indach/ (Accessed: 6 September 2021).

[4] Roberts, S. and Guariento, N. (2009) ‘*Building Integrated Photovoltaics: A Handbook*’, , pp. 68–70.

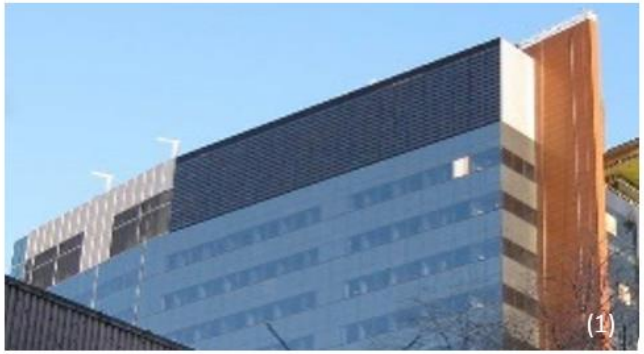
[5] Kalogirou, S. (2015) ‘*COST Action TU1205 (BISTS) Building Integration of Solar Thermal Systems-BISTS Examples*’, 1205(July), pp. 1–9.

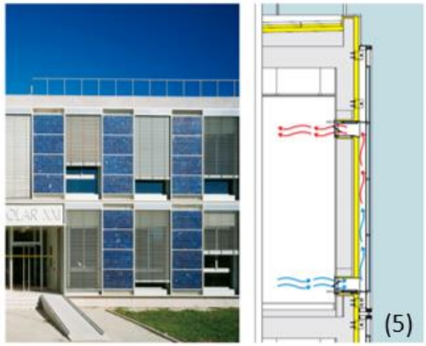
[6] FotoTherm (n.d.) *CS SERIES*. Available at: http://www.fototherm.com/en/our-products/cs-series/ (Accessed: 6 September 2021).

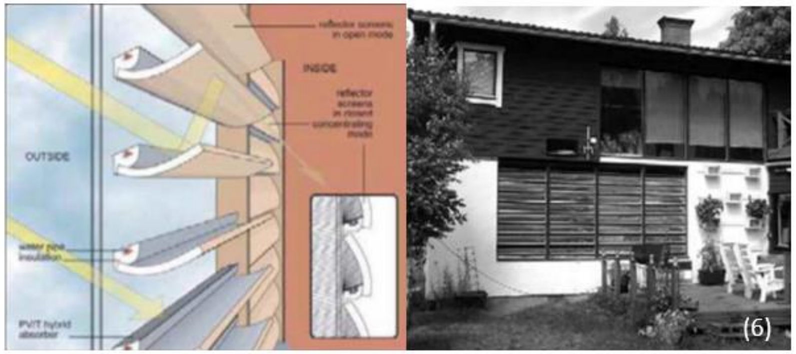
[7] Tractile (n.d.) *Award Winning Pearl Beach, NSW*. Available at: https://tractile.com.au/pearl-beach-case-study/ (Accessed: 6 September 2021).

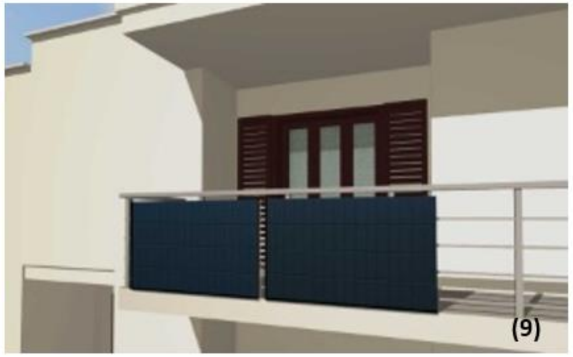
[8] FotoTherm (n.d.) *SOLAR BALCONY*. Available at: http://www.fototherm.com/en/our-products/solar-balcony/ (Accessed: 6 September 2021).

Figure_Apx 5. Pictures of the installations gathered in Table_Apx 5.



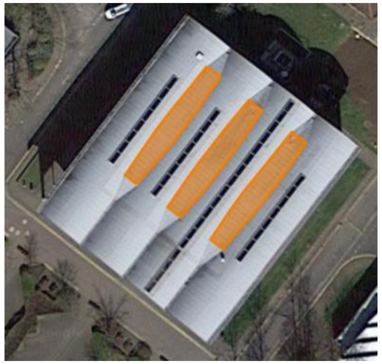
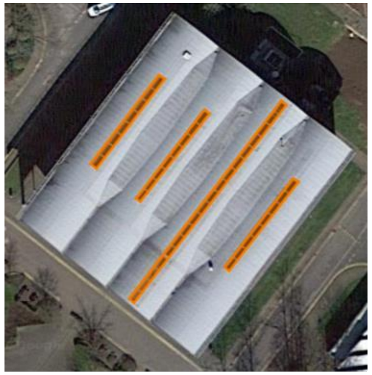


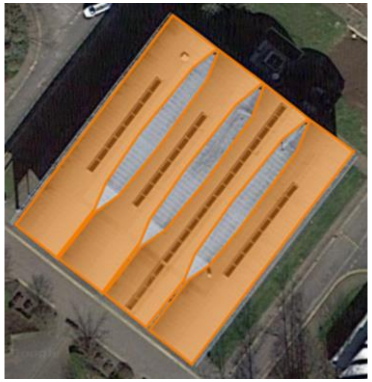


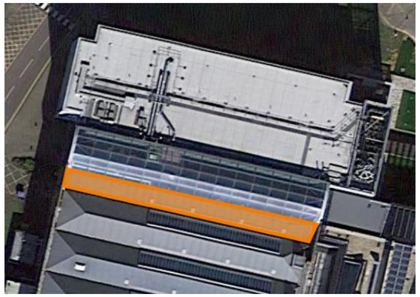


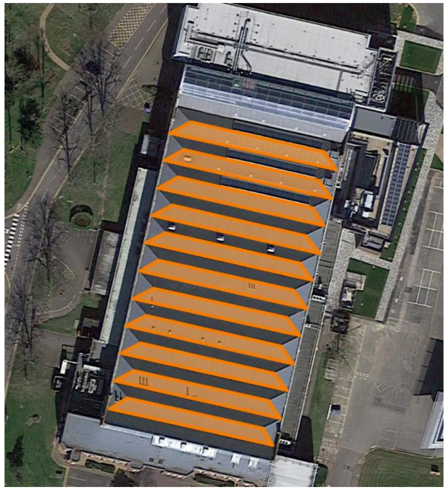
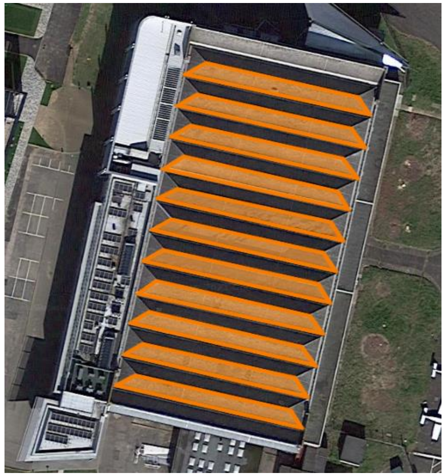
Appendix B Supplementary information for Chapter 5: Case Study at Cranfield University

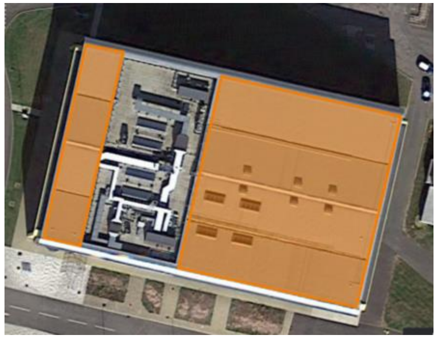
Table_Apx 6. Details of the installation and electrical production for each of the buildings chosen for the Case Study.

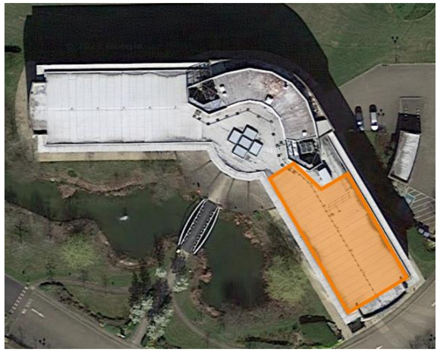
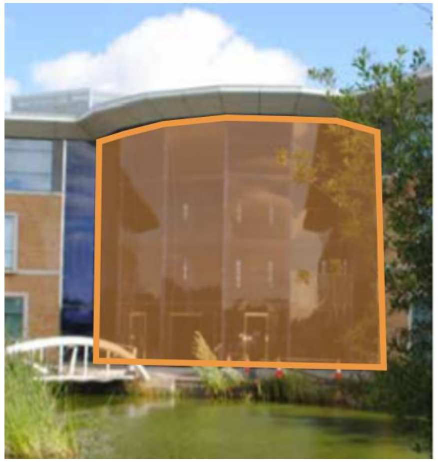
Building	Location of the BI facility	Considerations	Electricity production (MWh/year)
King's Norton Library – Building 55		▪ Total available surface: 255 m^2 ▪ Surface inclination: 0º ▪ Azimuth: -30º ▪ Used surface: 251 m^2 ▪ Number of modules: 152 ▪ Installed capacity: 46.2 kWp	40.4
		▪ Total available surface: 157 m^2 ▪ As it is a skylight, PV cells will only fill 50% of the module surface, so 76.5 m^2 available ▪ Surface inclination: 0º ▪ Azimuth: -30º ▪ Used surface: 73 m^2 ▪ Number of modules: 45 ▪ Installed capacity: 13.5 kWp	11.8

		▪ Total available surface: 1,400 m^2 ▪ Surface inclination: variable ▪ Azimuth: -30º ▪ Used surface: 1,382 m^2 ▪ Number of modules: 850 ▪ Installed capacity: 256 kWp	217.7
		▪ Total available surface: 280.8 m^2 ▪ Surface inclination: 30º ▪ Azimuth: -30º ▪ Used surface: 260 m^2 ▪ Number of modules: 156 ▪ Installed capacity: 46.8 kWp	46.8
C4D – Building 82		▪ Total available surface: 335 m^2 ▪ Surface inclination: 20º ▪ Azimuth: -30º ▪ Used surface: 299 m^2 ▪ Number of modules: 184 ▪ Installed capacity: 55.2 kWp	55.3

Vincent Building – Building 52a		▪ Total available surface: 175 m^2 ▪ Skylight: PV cells will only fill 50% of the module surface, so 87.5 m^2 available ▪ Surface inclination: variable ▪ Azimuth: 20º ▪ Used surface: 174 m^2 ▪ Number of modules: 108 ▪ Installed capacity: 25.2 kWp	31.2
		▪ Total available surface: 200 m^2 ▪ Surface inclination: 45º ▪ Azimuth: 20º ▪ Used surface: 190 m^2 ▪ Number of modules: 117 ▪ Installed capacity: 35.1 kWp	36.2

Whittle Building – Building 52		▪ Total available surface: 1206 m^2 ▪ Surface inclination: 45º ▪ Azimuth: 10º ▪ Used surface: 1098 m^2 ▪ Number of modules: 675 ▪ Installed capacity: 203 kWp	212
Building 83		▪ Total available surface: 1190 m^2 ▪ Surface inclination: 45º ▪ Azimuth: 10º ▪ Used surface: 1098 m^2 ▪ Number of modules: 602 ▪ Installed capacity: 181 kWp	190

AIRC – Building 320		▪ Total available surface: 1755 m^2 ▪ Surface inclination: 0º ▪ Azimuth: 10º ▪ Used surface: 1754 m^2 ▪ Number of modules: 1,078 ▪ Installed capacity: 252 kWp	283
		▪ Total available surface: 423 m^2 ▪ Surface inclination: 90º ▪ Azimuth: 10º ▪ Used surface: 416 m^2 ▪ Number of modules: 256 ▪ Installed capacity: 76.8 kWp	60.3
Martell House		▪ Total available surface: 520 m^2 ▪ Surface inclination: 0º ▪ Azimuth: 0º ▪ Used surface: 508 m^2 ▪ Number of modules: 312 ▪ Installed capacity: 93.6 kWp	80.2

		▪ Total available surface: 490 m^2 ▪ Surface inclination: 0º ▪ Azimuth: 60º ▪ Used surface: 482 m^2 ▪ Number of modules: 296 ▪ Installed capacity: 88.8 kWp	76.1
		▪ Total available surface: 125 m^2 ▪ Skylight: PV cells will only fill 50% of the module surface, so 62.5 m^2 available ▪ Surface inclination: 90º ▪ Azimuth: variable ▪ Used surface: 57 m^2 ▪ Number of modules: 35 ▪ Installed capacity: 10.5 kWp	7.7

Table_Apx 7. Savings on grid-electricity consumption, money and CO_2 emissions.

Building	Potential energy production (MWh/year)	Energy consumption in 2019 (MWh/year)	Percentage of consumption that would be covered by potential production (%)	Money savings (£)	CO_2 emissions savings (metric tons)
King's Norton Library – Building 55	316.7	1,186	26.7	68,597	224.5
C4D – Building 82	55.3	32	173.6	11,978	39.2
Vincent Building – Building 52a	67.4	2,773	2.4	14,598	47.8
Whittle Building – Building 52	212	2,380	8.9	45,919	150.3
Building 83	190	1,670	11.4	41,154	134.7
AIRC – Building 320	343.3	320.6	107.1	74,359	243.4
Martell House	164	580.9	28.2	35,522	116.3
TOTAL	1,348.7	8,942.4	15.1	292,127	956.2