MSc Program
Renewable Energy Systems

HOW TO BENEFIT FROM BIPV SYSTEM FOR DESIGNING ENERGY-EFFICIENT COMMERCIAL BUILDINGS

A Master's Thesis submitted for the degree of
“Master of Science”

supervised by
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Vienna, 23.03.2020

Affidavit

I, **MAHDIEH HOSSEINI**, hereby declare

1. that I am the sole author of the present Master's Thesis, "HOW TO BENEFIT FROM BIPV SYSTEM FOR DESIGNING ENERGY-EFFICIENT COMMERCIAL BUILDINGS", 102 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
2. that I have not prior to this date submitted the topic of this Master's Thesis or parts of it in any form for assessment as an examination paper, either in Austria or abroad.

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Abstract

Photovoltaic (PV) application is the most favorable power generation system over the world, due to the remarkable advantages of solar energy compared to fossil fuels. A proper PV installation serves more than 20 years and its natural source energy is generally available. Also, the maintenance cost of the system is either zero or very small. In contrast, fossil fuel is limited, terminable, environmentally destructive and expensive because of the high costs of the generation and maintenance.

Although building integrated photovoltaic is a relatively new technology in the industry of PV, the global market of BIPV is rapidly growing. "The global building-integrated photovoltaics market size is expected to reach USD 36.74 billion by 2025, (…) It is projected to expand at a compound annual growth rate (CAGR) of 18.8% from 2019 to 2025." (Grand View Research, June 2019 Report ID: GVR-1-68038-301-0). Proper regulations and financial supporting schemes from authorities are the main motivational drivers of expanding the BIPV installations.

Considering the growth of the building industry and the remarkable potential of commercial buildings for PV mounting, this piece of work tries to present scientific investigations on how to improve the PV integration into the built environment.

Table of contents:

1. Introduction

Energy demand and supply are one of the world’s biggest challenges, which leads to the constant development of energy production and supply systems. Through different renewable energy sources, solar energy has always been on the top of the list, regarding the fact that it’s the most available and cheapest source in almost every place over the world. The popularity of solar energy is due to the increasing number of photovoltaic installations.

The technology of PV application for the buildings started in the 1970s and has grown up along with the growth of demand for clean energy. Building Integrated photovoltaic is a relatively new technology in the industry of PV. This advanced technology is focusing on power generation and the integration of the energy generation systems and the building foundation.

Building integrated photovoltaic (BIPV) is the most promising factor towards achieving the target of zero energy buildings in 2020 and helps to maintain the sustainable development goals. Regardless of how close we are now to the target of zero energy buildings, it has proved that the buildings can become at least 40% more energy efficient. Besides, making the buildings more energy efficient is essential since the total building growth is predicted to be 60% more than today by 2040 (IEA news, October 2018).

The urgent need for clean energy and the great potential of the buildings for energy generation have required building designers to engaging the architectural technology with the PV energy system.

1.1. Core objectives of this work

Having said that energy generation is an urgent demand in the world, but shifting to renewable sources is as important as producing and supplying energy. Raising awareness about the benefits of clean energy plays a key role in shifting to renewable energy sources.

PV installation is the most favorable system in the built environment. According to task 7 of the International Energy Agency (IEA), integration of PV into the buildings will increase PV developments in the future which requires collaborating of architects, building engineers, and urban planners. Task 7 incorporates several groups of professionals including PV specialists, building designers, utility specialists and every profession involved with PV technology.

The main aspect of Task 7 is the integration of PV systems into the built environment by considering PV system through architectural designs the roof-mounted and façade-mounted elements. Also, by considering other potentials in the built area for PV mounting, such as noise barriers, parking areas, and railway canopies. (Task7, IEA)

Market factors of the technical and non-technical kind are also mentioned in Task 7. The Task is focused on four technical fields and their activities, as follows:

- *"Architectural Design: A database of existing PV projects, case studies, architectural books, design tools.*
- *Systems Technologies: Building integrated, non-building structures, guidelines and safety issues, PV thermal systems, new electrical concepts, reliability and maintenance, interconnection issues, electrical design issues.*
- *Non-technical Barriers: Non-technical barriers, potential, economic issues, marketing and publicity strategies.*
- *Demonstration and Dissemination: Demosite, conferences, design competition, dissemination strategies, education and training."* (International Energy Agency. task 7, December 2001)

This scientific work would first clarify what are the most effective factors of energy consumption of buildings, follows with the investigation of technology of building-integrated photovoltaics including the advantages and challenges of this technology. The most highlights of this work are how the technology of BIPV could improve the energy efficiency of the built area (by focusing on commercial buildings).

1.2. Benefits of improving energy efficiency of the buildings

Governments, building owners and utilities would all benefit from the energy efficiency of the buildings. The following table shows the classified benefits of energy efficient buildings for the main three target groups. Apart from that improving the energy efficiency of the buildings creates jobs as a number of professions and skills are required to improve the energy performance of the built environments. And job creation leads to social and economic growth.

Table.1 Benefits of improving energy efficiency of buildings. (own table)

Governments	Improving the quality of air, improving the quality of health and reducing the health costs of the society, developing the gross domestic product, improving tax bases, providing energy security, Providing availability for resourcing of, nonrenewable energy sources (Krarti, 2018).
Building owners	Reduction of costs and reduction of maintenance, improving durability, improving the indoor comfort, improving the health, increasing the value of the property, improving productivity and self-sufficiency (Krarti, 2018).
Utilities	Operational benefits by decreasing customers' turnovers, improving energy generation, improving the efficiency of the transmission system, expense benefits and reduction of system capacity limitations (Krarti, 2018).

1.3. Structure of this work

The main idea of this work is to represent how BIPV technology improves the energy self-sufficiency of buildings. To succeed in this purpose all aspects of PV power generation must be evaluated, as well as the heating, ventilation and air conditioning system (HVAC) and indoor comfort of the buildings.

Climate condition is different over the world, and architectural designs should be climate-responsive, also features of global solar irradiation like daily and monthly sunshine durations would influence on the efficiency of PV systems in each location.

By simulating one building that is equipped with the BIPV system and analyzing the performance of the same building in three locations of Vienna, Tehran, and Melbourne, this work tries to demonstrate how the same technology would respond to the energy requirement of buildings in different regions.

Despite the great advantages of BIPV technology, there are identified challenges regarding this system. Dealing with challenges related to weather like wind, rain and air mass is only a part of the issues. Other issues such as structural support, architectural design, materials, PV mounting and sustainability of the grid, are other considerations regarding this technology.

Financial aspects and features of sustainable development are the main incentive factors to decide for PV system installation. in chapter 9, simulation of a BIPV system is carried out in three developing cities to determine how much of the building's demand can be covered by the proposed PV system. This simulation would clarify whether the system is economically viable.

Achievements of this scientific work contain lessons learned from a number of BIPV applications, and will hopefully provide useful knowledge towards BIPV system developments and the future of this technology.

2. Background information

Solar systems are the fastest growing sector of renewable energy sources. During sunshine hours, a PV module directly generates electricity from irradiances of the sun. The popularity of the PV system is due to the availability of the solar source and other features of solar systems such as low price, making no sound and no air pollutions and minimal maintenance.

Producing the first photovoltaic cells started in the 1950s and during the 1960s PV panels were used for providing electricity for earth-orbiting satellites. Owing to the manufacturing developments in the 1970's the commercial business of solar panels started. Hence the number of PV panel installation increased. But the global growth of photovoltaics occurred mainly in the 21st century.

Different types of PV panel installation are:

- Grid connected ground-mounted photovoltaics (PV power plant)
- Grid connected roof-mounted photovoltaics (figure1), usually by lay- on technology.
- Grid-connected building integrated photovoltaic (figure.1)
- Off grid photovoltaics (stand alone) with battery storage (figure.2)

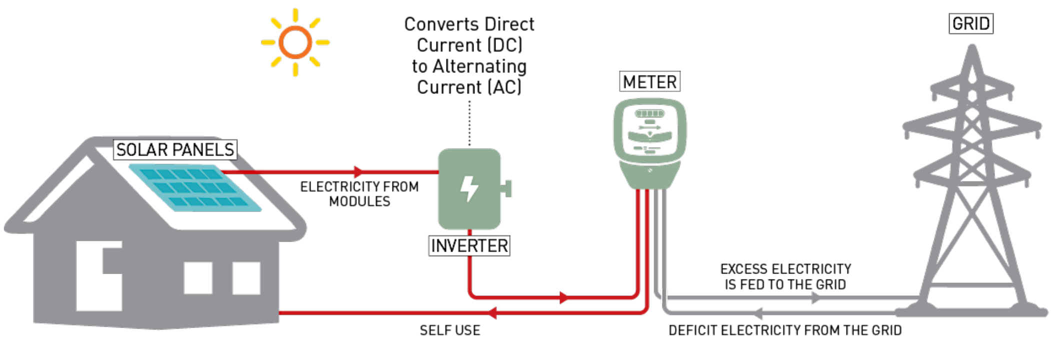


Fig.1 Grid connected – roof mounted PV
Source: vikramsolar

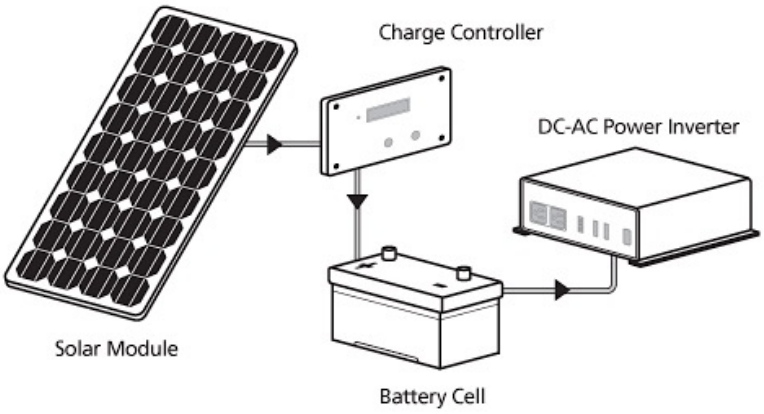


Fig.2 Off-grid photovoltaics (stand alone) with battery storage.
source: samlexsolar

Off-grid PV system includes PV panel(s), charge controller, battery, and power inverter. When the PV panel converts sunlight to direct current electricity (DC), the charge controller automatically regulates the charging level of the battery. Battery stores the produced DC energy that can be used during the night time and cloudy days when there is no sunlight available. The invertor converts the DC power produced by the PV panel into alternating current (AC) power to supply the building.

3. Technology of building integrated photovoltaics

Solar panels turn the photons of the sun into the DC electricity, then the inverter turns the DC electricity into alternating current (DC to AC electricity conversion). PV panel or PV module is a group of PV cells that are encapsulated and connected to create a DC electrical unit. Arrangement of several PV panels could capture the maximum portion of sunlight to generate electricity. PV panels are designed to install in outdoor areas, they are manufactured in different sizes and need to be longlisting.

PV cell is the component where the sunlight into electricity conversion happens. The process of producing electricity by the solar cell is called the photovoltaic effect, which is a combination of chemical and mechanical processes. When the light reaches the PV cell, a portion of the light gets absorbed within the semiconductor material (silicon). An electric field is created by doping the silicon with impurities such as phosphorous or boron elements to make an N-type or P-type zone. Then the electrons of absorbed light flow in a certain direction. Metal contactors are placed on the top and the bottom of the PV cell to make an external circuit where the produced flow can pass through and be put to work. The current is captured and transferred to wires.

The average efficiency of PV cells is around 20% which means nearly 80% of the sunlight that reaches the PV cells is not being converted to electricity but converted into heat.

3.1. PV materials

Generally, PV cells can be characterized in two categories, crystalline silicon solar cells and thin-film solar cells. Silicon-based PV cell types are monocrystalline silicon and polycrystalline silicon. New types of PV cells are being developed.

3.1.1. Monocrystalline silicon

Monocrystalline silicon cells are also called single crystal cells. The cells are manufactured from a crystal ingot with high purity by crucible drawing process technique (Czochralski) and with a diameter of 125mm or 156mm. The ingot is cut into thin slices to be used for making PV cells. Edge-defined film-fed crystal growth and string ribbon process are other methods for making Monocrystalline silicon cells.

To increase the light absorbent and improve the efficiency, the cell is coated with a thin anti-reflection element, which is either silicon nitride or titanium oxide. This creates a dark blue appearance for the cells. To omit the dark blue appearance for BIPV façade an option is skipping the anti-reflection coating. This way the appearance would be a natural dark grey but reflection losses would increase from 3% to 30%. Other types of anti-reflection coating would give different colours to the cells but again reduces the efficiency percentage. Figure.3 is a schematic of a typical crystalline silicon solar cell (Roberts & Guariento, 2009).

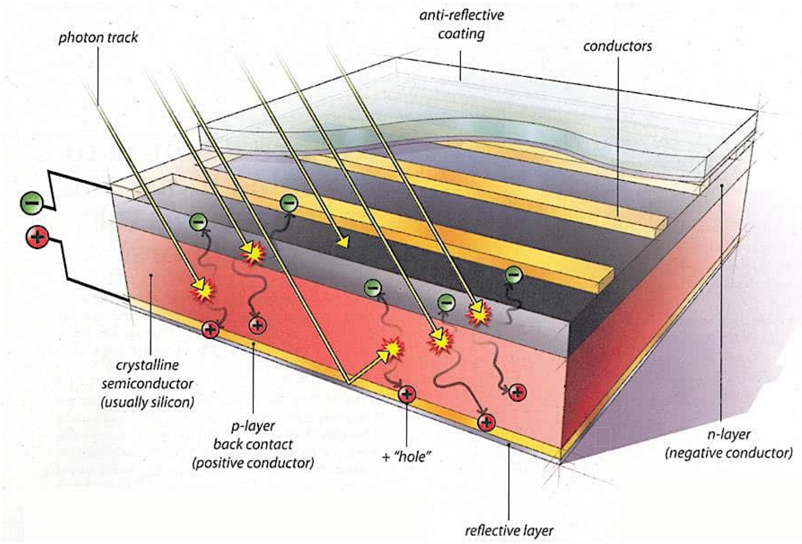
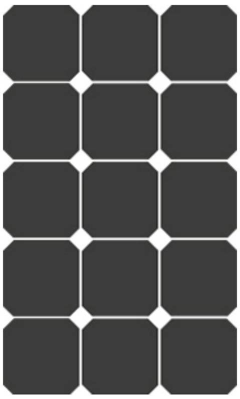
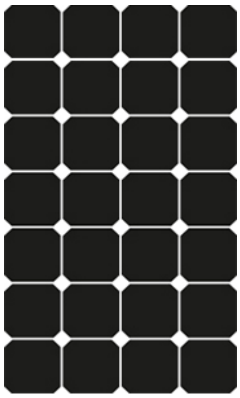
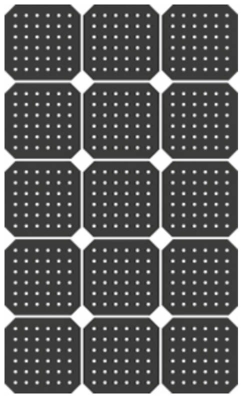
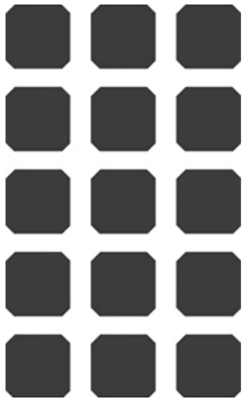
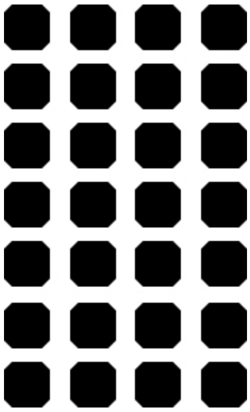
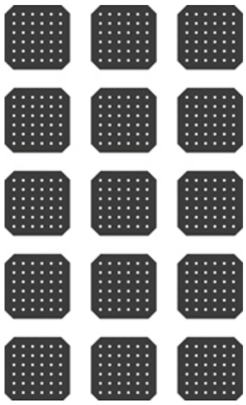


Fig.3 Schematic of a typical crystalline silicon solar cell
Source: Solar Energy Industries Association, 2013

The back-contact layer is usually aluminium coating to increase the cell efficiency, Varied types of latest monocrystalline cells are shown in the following tables.

Table.2 Monocrystalline cell types. (source: ertexsolar)

	
Monocrystalline semi-quadratic 156 x 156 mm cell distance: 5 mm	Monocrystalline high-efficiency semi quadratic 125 x 125mm cell distance:5 mm

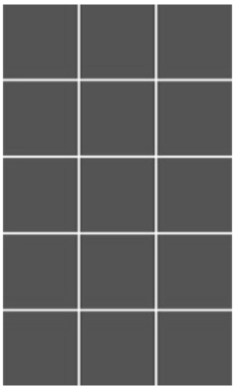
	
Monocrystalline semi-transparent perforated. semi-quadratic 156 x 156 mm cell distance: 5 mm	Monocrystalline semi-quadratic 156 x 156 mm cell distance: 50 mm
	
Monocrystalline high-efficiency semi quadratic 125 x 125mm cell distance:50 mm	Monocrystalline semi-transparent perforated. semi-quadratic156 x 156 mm cell distance:50 mm

3.1.2. Polycrystalline silicon

Polycrystalline or Multi-crystalline silicon is a type of PV cell that is made by melting the main material and placing it in a cubic mold. As the silicon material solidifies, a number of crystal grains are created in different sizes from a few millimetres to a few centimetres. There will be boundaries between the grains that reduces the efficiency of the cell but only a little. The next step when the ingot is made is cutting the ingot into bars and then slicing the bars into thin wafers to be used for making the cells, the same as making monocrystalline silicon cells.

The price of these cells is lower than monocrystalline cells and their efficiency is slightly fewer. New polycrystalline cells are usually cut in large size of 15.6 x15.6 cm to provide lower costs and higher overall efficiency of the PV module. The coming table shows the Polycrystalline silicon PV types (Roberts & Guariento, 2009).

Table.3 Polycrystalline cell types. (source: ertexsolar)

	
Polycrystalline – Full quadratic156x156mm cell distance:5 mm	Polycrystalline – Full quadratic156x156mm cell distance:50 mm

3.1.3. Thin-film PV cells

Thin-film cells are made by placing thin layers (thin-film) of photovoltaic material on a substrate which is glass, metal or plastic. Attachments of the PV cells are the entire fabrication process because at the same time the PV module is made. The active semiconductor materials of these cells are amorphous silicon (a-Si), copper indium selenide (CIS) and cadmium telluride (CdTe). Regarding the fewer used material and highly automated manufacturing of thin-film modules they are less expensive than crystalline silicones, however, the efficiency of this technology is lower than crystalline silicon cells as well (Roberts & Guariento, 2009). The schematic of a thin-film silicon PV module is shown in figure 4.

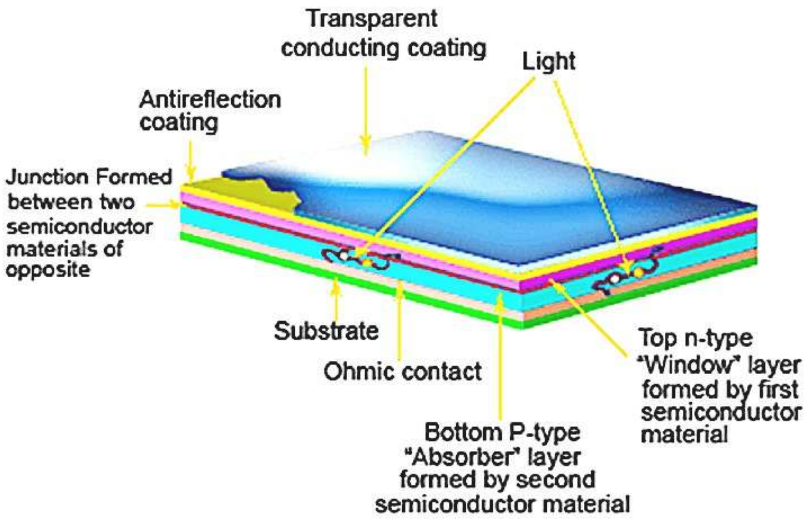


Fig.4 Schematic diagram of a thin film silicon PV module
Source: Vahid Mirzaei, Mahmoud Abadi, 2015

3.1.4. High efficient PV cells

The technology of photovoltaic is improving and new types of PV cells with high performance are being developed, such as Multi-junction solar cells, Heterojunction solar cells (HJT PV) and GaAs semiconductor PV cells.

3.1.5. Multi-junction solar cells

Multi-junction solar cells are more efficient than single-junction cells since they are made of multiple layers to be capable to absorb different wavelengths of sunlight. Although these solar cells have more potential at converting sunlight to electricity, they are not commercially pragmatic yet due to the high production costs and the ongoing research and development regarding these new types of cells.

A multi-junction solar cell is a multiple layer of the solar cells with more than one positive-negative junction, which means the accumulated materials used in this cell are optimized to absorb different frequencies of sunrays. The mechanism of this cell is based on multiple layers of semiconductor materials, each layer responses to a different wavelength of sunlight to produce direct electric current, therefore they would be practically capable of convert bigger portions of sunlight in compared with single-junction cells (energysage).

Like the normal silicon solar cells, multi-junction solar cells produce electricity through the **photovoltaic effect** process (described in chapter 3). The photovoltaic effect can be summarized in four main steps:

1. Light reaches the PV cell and a portion of the light gets absorbed within the semiconductor material (silicon).
2. The electrons of the absorbed light flow through the p-n junction within the semiconductor layers, which makes an electrical current.
3. Metal contactors on the top and the bottom of the PV cell make an external circuit where the produced flow can pass through.
4. The produced current is captured and transited to the connection wires.

The only difference is that single-junction solar cells have one p-n junction to direct the flow of electricity produced by hitting the semiconducting material with sunlight, while in a multi-junction solar cell, there are multiple p-n junctions that can enforce a flow of electricity.

The structure of a multi-junction solar cell is shown in the following figure. Materials like gallium indium phosphide (GaInP), indium gallium arsenide (InGaAs), and germanium (Ge) are used to create separate layers of semiconductors that each response to a different wavelength of sunlight (energysage).

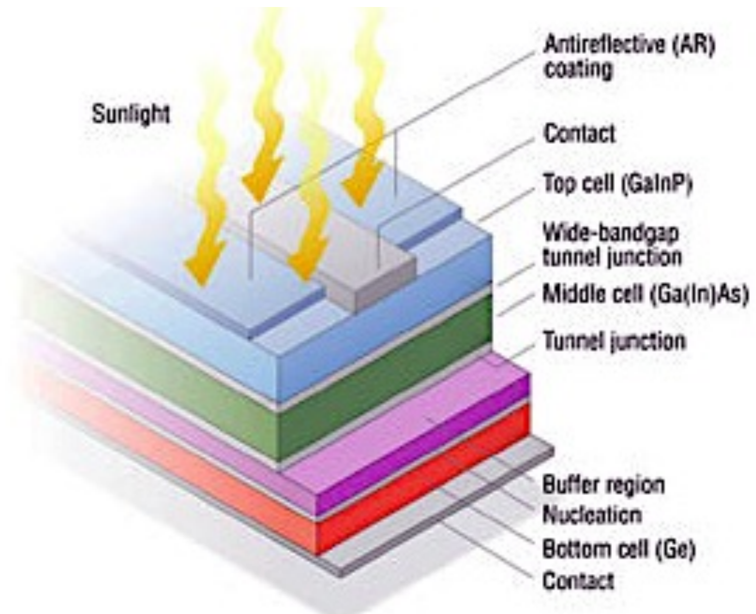


Fig.5 layers of a multi-junction solar cell. Source: Office of Energy Efficiency and Renewable Energy Research (Image: Alfred Hickes/NREL)

3.1.6. Heterojunction solar cells (HIT PV)

Silicon heterojunction solar cell is a combination of thin amorphous silicon layers and the crystalline silicon wafer. The thin-film layers are deposited on the silicon wafer, and this design enables 20% higher energy conversion.

"*The key feature of this technology is that the metal contacts, which are highly recombination active in traditional, diffused-junction cells, are electronically separated from the absorber by insertion of a wider bandgap layer. This enables the record open-circuit voltages typically associated with heterojunction devices without the need for expensive patterning techniques."* (Wolf et al., 2012:7)

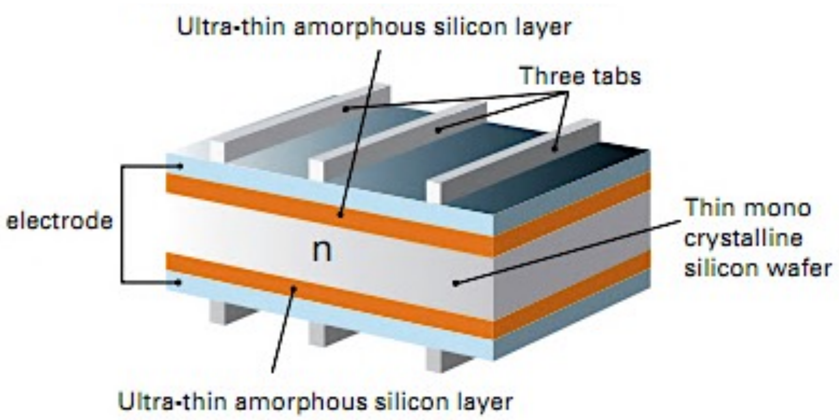


Fig.6 HIT cell technology combines amorphous and crystalline silicon into one cell
Source: SANYO HIT-N235SE10 Flier

3.1.7. Gallium Arsenide PV cell

Gallium arsenide (GaAs) is a very common semiconductor material used in PV cells. The popularity of GaAs is due to its high electron mobility which provides this cell with 30% efficiency. This semiconductor component can be used in single or multi-junction PV cells and the manufacturing concentration is on developing GaAs thin-film solar cells. This is making gallium arsenide a reference system for thin-film PV cells (photonetc).

Gallium arsenide thin-film solar cells are known as high-efficient, flexible, lightweight, colour adjustable and elastic shaped cells. Also, gallium arsenide batteries, have better temperature resistance compare to silicon photovoltaics.

However, there are some of the disadvantages regarding using gallium arsenide thin-film PV such as:

- High costs
- Battery attenuation, since Gallium arsenide batteries need to be fully cooled down to enable their power generation efficiency and to slow down their thermal attenuation
- Package complexity since gallium arsenide has more breakable physic compare to silicon material, which makes it break easier when it's processed. (AZoM, 2002)

3.1.8. Comparison of PV Types Efficiency and Area requirement

The PV industry is improving quickly and constantly over the world and new generations of high-efficient PV cells are being offered to the market. According to the report from the Center for Sustainable Systems of the University of Michigan, in 2018 the new high-performance photovoltaic cells are being produced with the features shown in table 4.

Table.4 PV Technology Types and Efficiencies
Source: Center for Sustainable Systems. University of Michigan (2018), Photovoltaic Energy

PV Type	Cell conversion efficiency	Module conversion efficiency
Monocrystalline Silicon	25.0%	14 – 16%
Polycrystalline Silicon	21.3%	14 – 16%
Gallium Arsenide (GaAs)	27.5 - 29.1%	not applied
Thin-film (a-Si)	13.6%	6 – 9%
Thin-film (CdTe)	22.1%	9 – 12%
Thin-film (CIS /CIGS)	22.3%	8 – 14%

“*ertex solartechnik GmbH”* is a first-grade Austrian company specialized in building integrated photovoltaic technology, produces high efficient PV modules and recommends PV products as shown in the following table. In this table, different PV cell types are offered based on their efficiency, transparency factor and area performance.

Table.5 Different PV cell type, sizes, efficiencies, power and area performances (Data: ertexsolar catalogue)

PV Type	Dimensions mm	Efficiency	Area Performance W/m2	Cell Power W/cell
Polycrystalline	156 x 156	16%	125	3.7 – 3.9
Monocrystalline	156 x 156 125 x 125	18%	130	4.2
Monocrystalline – high efficient	125 x 125	22%	155	3.04 – 3.10
Monocrystalline – semi transparent	125 x 125	17%	105	2.01
aSi thin-film OPAK (PV panel)	576 x 976	5%	55	32
aSi thin-film THRU 10% or 20% (PV panel)	576 x 976	4%	47-43	27

3.1.9. Colour and Texture

To absorb the maximum portion and reflect a minimum portion of sunlight, PV cells usually have a dark appearance. Monocrystalline PV cells are usually black, blue or grey and polycrystalline silicon cells are medium to dark blue. Whereas thin-film PV cells typically have dark mat appearance, they are presented in dark brown, black and grey. Different anti-reflection coating techniques provide different appearance colours of PV cells. But the lighter colours would decrease the efficiency of the cell between 15-30% since brighter colours reflect more portion of the light. The glass laminate not only supports the PV cells but also can provide different appearances for the PV panel using special glass embellish techniques.

Ceramic silk-screen fritting is a common technique, by applying the ceramic silk-screen to the backside of the laminated PV module, a pleasant look with the desired pattern would be given. The glass laminated PV module consists of a built-in layer of a printed image or a coloured surface that is installed below the silicon cell. This technique is especially suitable to provide look-alike glass units to be installed instead of a PV module in inappropriate positions such as permanently shaded areas. It also provides a flawless look for the whole PV module arrangement (Roberts & Guariento, 2009).

Fig.7 Coloured PV cells (source: SolSky)

3.2. PV module

One solar power unit is the arrangement of 30 or more PV cells that are connected in a series. This unit is called a PV module or PV panel, which is a basic form of building integrated photovoltaic. A high-performance monocrystalline PV panel consists of 36 cells (size: 156 x 156 mm) has a peak voltage of 21.2 Volts and an output power of 150 Watts.

The produced DC electricity by the module can be either converted to AC electricity by using a PV inverter or be directly used to charge a battery in case of off-grid application. To protect the PV module against mechanical stress, weather, and humidity, they must be encapsulated. The front glass (cover) of the PV module must be a high-performance transmitter, also it must be pre-stressed to bear the high thermal loadings (Simon & Guariento, 2009).

The transmission efficiency of the glass cover is usually around 92%, and the rest 8% is being reflected. By applying an anti-reflection coating the reflection rate would be decreased around 3% which increases the transmission efficiency. The standard thickness of the glass cover is 3 – 4 mm, and for large modules, it could be increased to 10 mm (Simon & Guariento, 2009).

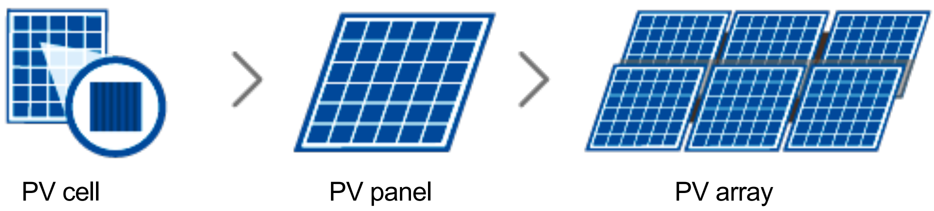


Fig.8 Components of a solar panel system
Source: Greenmatch, 2020

3.3. Components of standard complete PV modules

3.3.1. Encapsulation

The total life span of PV modules is 30 years and more, and manufacturers try to produce high-performance PV modules to guarantee that they would produce more than 80% of their nominal power during 20 - 25 years of their operation. Achieving such high features that last in a long period of time provides a durable packing technique to support the module from the environment, considering that PV modules are exposed to the environment and could be damaged by physical stresses, weather, humidity, etc. This makes encapsulation an essential part of the PV module manufacturing (Roberts & Guariento, 2009).

Encapsulation has been developed in a number of techniques. The most common encapsulation is done with cross-linkable ethylene vinyl acetate (EVA), which means laminating the PV cells between EVA films via the process of vacuum and compress in up to 150 centigrade degrees' temperature. During this process, the EVA films get melted under pressure and high temperature and flow throughout the PV cells and cover whole the cells.

Generally, the back-side of the PV modules encapsulated with EVA is a thin opaque film, but the back-side could also be a glass cover to provide transparency, in this case, the PV panel is called glass-glass laminate. In order to maximize light penetration, PV panels can be integrated into double glazed units. PV units generally produce high temperatures due to absorbing heat by black appearance. Therefore, the glass laminate of a single and double glazed units must be heat treated (Roberts & Guariento, 2009).

Another encapsulation medium is Teflon, but since Teflon is a UV resistant material it has a lower reflectivity than the glass laminate. Teflon provides protection for the front glass and the module can just be laminated to e conventional tempered glass. The thickness of the Teflon layer is only 0.5 mm but this very thin layer conducts more heat than the thick front glass which is considered the weak point about the Teflon encapsulation. However, it's usually used in smaller size modules such as PV roof-tiles (Roberts & Guariento, 2009).

Another encapsulation medium is Resin which provides a glass-look module. Resin encapsulation is also considered for the sound-absorbing glaze. Thermoplastic polyurethane (TPU) films are also used to encapsulate PV cells. TPU is used to encapsulate the window screens of cars as well.

Thin-film encapsulation is as important as the other types of PV modules encapsulation, although the thin-film cells themselves are the PV module, the module still is a raw unprotected material and needs encapsulation. EVA lamination technique is the standard encapsulation technique for thin-film modules, the same for crystalline modules.

Lately, non-encapsulated PV modules have been developed. In these modules, the PV cells are placed inside a cavity of a double-glazed unit which is filled with inert gas, and electrical connection is achieved by compacted junctions.

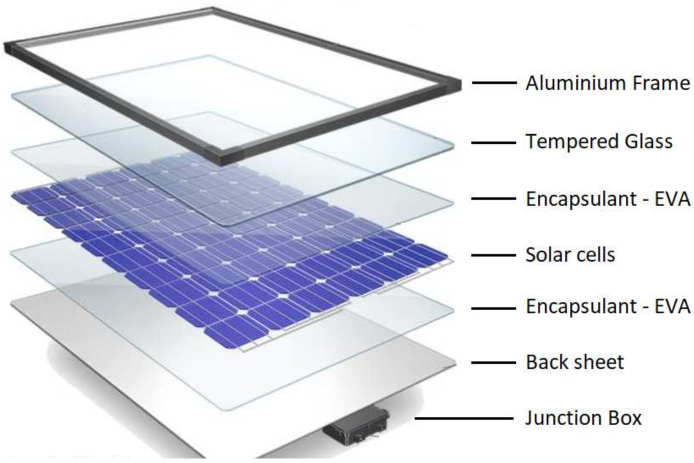


Fig.9 The 6 main components of a solar panel - Image Credit Trina Solar
Source: Jason Svarc, 2018

3.3.2. Electrical contact points (cable outlets and junction boxes)

The connections between the PV cells inside the module and the electrical points are through either a glass panel with holes on the backside or a film layer that is penetrated at the backside of the module. A junction box is placed at the entry which must have minimum protection at IP 54 and protection class II. BIPV modules usually have the flying leads, ready to be connected to the other leads by plugs and sockets. Cables connect the modules together by looping into one module to another. This linking pattern is called daisy-chains.

Usually, modules are built and transferred with connection components from the factory. They can be easily plugged together and be installed and there is no need to open the module junction boxes. There is another option for costume-made modules to turn the cables out along the edges of the glass. This especially works when the vision of the junction box on the back of the module is not desirable like for the façade mounted modules (Roberts & Guariento, 2009).

3.3.3. Standard modules and test standard

Standard PV modules are modules that are designed and produced at the lowest cost to produce the maximum possible portion of energy. They are mostly laminated in glass film and the final modules are supplied with or without a frame (usually aluminum frame). Crystalline cells are typically square shape sometimes with chamfered corners so that they can be arranged with minimum gaps and prevent wasting the space. The typical cell size is 10-15 cm and a typical standard module consists of 36 to 216 PV cells holding a peak power specification of 100-300 WP.

PV cells are arranged in different patterns in a module but usually are arranged in 4 to 8 rows in rectangular forms and lines of 36 to 72 are connected in series. Larger PV modules consist of 2 or 3 of these lines connected in parallel.

Standard PV modules are approved by international standard certification. The relevant standard for crystalline silicon modules is IEC 61215 along with the full title of the module, type of the module and design qualification of the module. For thin-film modules, the relevant standard is IEC 61646. These standards are accepted as quality marks.” (Roberts & Guariento, 2009)

3.3.4. Cell arrangement and transparency

The great point about the transparency option is that transparent and semi-transparent modules provide the designer with the possibility of a wide range of combining energy production with natural lighting and light effects. Glass laminated modules are known as semi-transparent modules or light-filtering since they let the light pass through. Considering that crystalline silicon cells are opaque, the light can only pass through the space between the cells which is something between 1-30 mm. Electric wires inside the modules are sort of hidden since they are only visible from a very close distance.

One technique for providing semi-transparent crystalline cells is covering the cells with small perforations which requires special process on both sides. And for the thin-film modules besides increasing the space between the cells, some lines of material can be arrayed perpendicular to the other cell strips. This provides a delicate checked pattern that gives transparency and almost no color appearance to the module besides providing a transmission value of 10 to 15% (Roberts & Guariento, 2009).

However, considering the semi-transparency option by increasing the space between the cells, would increase the area needed for the module to provide the expected amount of energy.

3.4. Flexible and curved PV modules

Along with developing thin-film photovoltaics the possibility for application of flexible solar panels has increased, including the application of solar panels on irregular curved surfaces. To maintain the efficiency rate in the arrangement of solar panels or curved surfaces, geometric computer-aided design (CAD) tools and irradiation analysis tools are required.

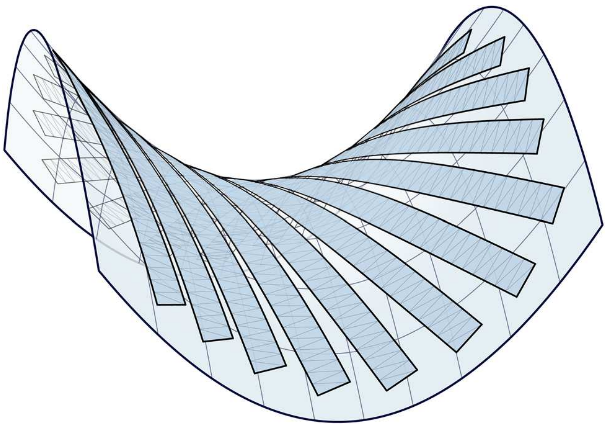


Fig.10 A series of strips approximating a hyperboloid surface
Source: Abel Groenewolt et al., 2016

Crystalline PV cells are proper options for curved modules with a minimum radius of 0.9m. These are done by placing the crystalline PV cells between the curved finished modules or the curved sheets. Whilst thin-film PV modules are flexible and they can be rolled to be placed on to flexible and curved layers (Roberts & Guariento, 2009).

However, flexible and curved modules should be laminated on a fluent and smooth materials instead of hard glass. Such as metal and synthetic foils or synthetic resin and glass textile membranes. Flexible PV modules are light weighted and ideal to be integrated into the curved roofs, constructions with arched elements and awnings.

As mentioned before, this technique requires the geometric plan of flexible PV modules on curved surfaces as well as the arrangement pattern of the modules on such a surface which are done by geometric CAD tools. By linking the geometric output to solar analysis software, plenty number of design options can be established considering the elements of panel dimensions, orientations, solar insolation potential and panel curvature. Also, a combination of geometric output and solar analysis provides essential data for the electrical design of the PV system.

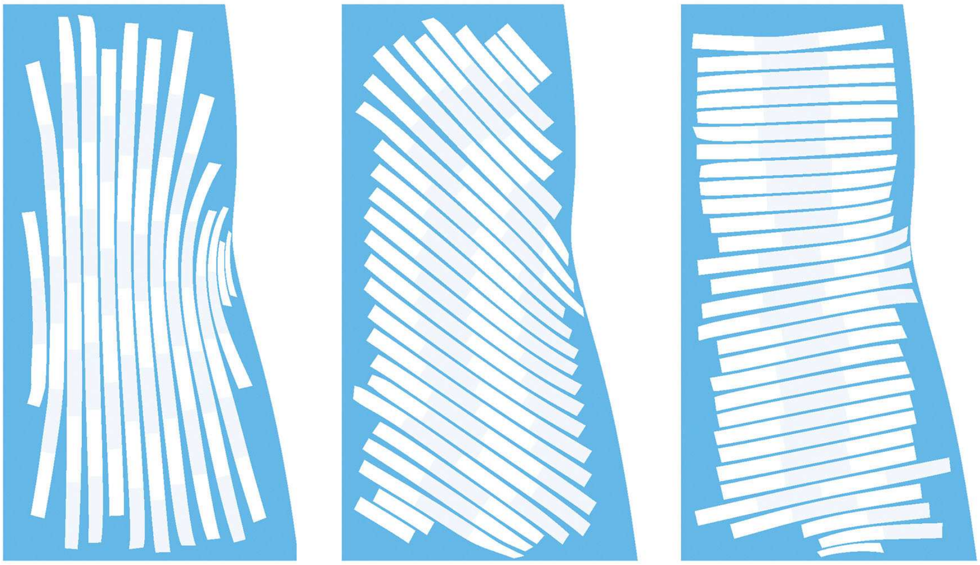


Fig.11 Strip arrangements using various starting angles. From left to right: 90°, -30°, 15°
Source: Abel Groenewolt et al., 2016

3.5. Module specification

Module specification is equal to the peak power specification of the module that is shown as watts peak or (Wp). This rate is determined by standard test conditions. These conditions are set while the PV module is completely facing the sun on a clear sunny day at the exact noon when the sun is around 60 degrees above the horizon and while the air temperature is zero degrees. These conditions are defined as:

- *"The actual temperature of PV cells (25 °C or 77 °F)*
- *The intensity of radiation (1kW/m2).*
- *The spectral distribution of the light (air mass 1.5 or AM 1.5, the spectrum of sunlight that has been filtered by passing through 1.5 thickness of the earth's atmosphere)."* (Roberts & Guariento, 2009: 30).

3.6. Sun trackers

Sun tracker or solar tracking system is a device that turns the PV modules towards the sun to provide the modules with receiving the maximum irradiations. A solar tracker system has three main components: the mechanism, driving motors and tracking controller.

Mechanism: is the component responsible for the accuracy of the tracking. The life span of this component must be equal to the PV modules and it must be designed the way to withstand the harsh weather conditions

Driving motor: is based on the solar tracker system. Solar tracking systems are distinguished as active or passive mechanisms. The active driving mechanism is usually an electric motor AC or DC or a hydraulic system. Whereas passive driving mechanism is usually the gravitational system. AC electric motors are the most common driving mechanisms since they control the accuracy of the rotations. For a one-axis solar tracker one motor and for two-axis solar tracker two motors are required (Cardeña & Luque, 2018).

Solar tracker controller: Based on the control mechanism, solar trackers are classified either as those orient the PV modules according to pre-computed sun trajectories which are called open-loop control, or the solar trackers that are equipped with solar radiation sensors to control the orientation of the tracking system that is called closed-loop control.

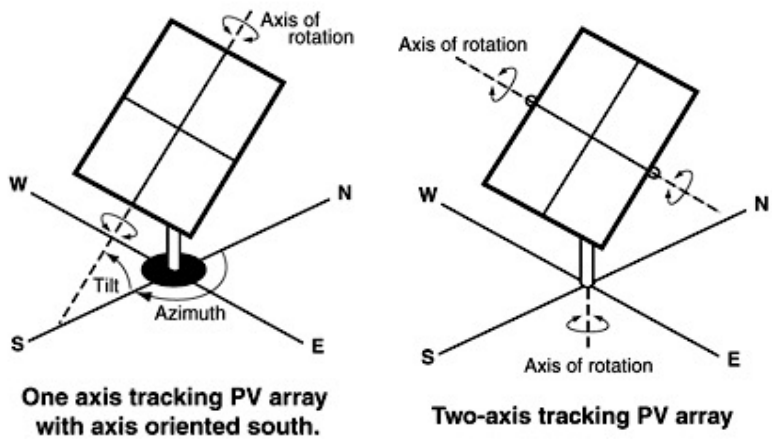


Fig.12 One- axis and two-axis tracking system schematics
Source: DR. BASHER et al., 2011

Commercial buildings are great options for PV installations. Statistics of the three given developing cities in this work show that; in Vienna, the total commercial property space is 250.000 m2 (Office Market Report in Vienna, spring 2019). In Melbourne over the past 10 years, a gross average of 120,000 square meters of new office supply has been added to the market each year (Colliers International Research). In Tehran, the growth of shopping malls and office buildings has been also remarkable during the past decade.

3.7. PV maintenance and replacement

After mounting the PV system, a maintenance program is required to make sure that PV arrays are working at the best performance. So that any faults of the system would be notified and corrected. The maintenance program is usually planned one of these three patterns:

- Monthly basis (check and report the electric output)
- Once per year (visually inspect the PV arrays)
- Once per year (clean the arrays and remove soiling)

The visual inspecting of arrays is essential to identify the problems such as physical damages or failures of the PV modules through the lamination process.

One PV array consists of several electrical parts that must work together efficiently. In the past electrical problems of PV arrays were concerning regarding the inverters, but the high-level design of the mature inverters has improved their reliability, also adding features like recording the electrical parameters and logging errors are now available to boost the performance of the PV inverters. These electrical problems can be occurred in the open circuit of a module or can be due to the corrosion of one connection to the inverter which fails the invertor to generate the AC output. This problem will be identified as a reduced monthly output comparing to typical output value for that specific time of the year (Roberts & Guariento, 2009).

The impact of soiling is very important since it causes the loss of output. This problem is very much dependent on the location and the air quality. Regularly rainstorms wash the dust and pollens away, but sticky dirt would stay during the rainstorm and should be removed manually. So, the solution for the soiling impacts is yearly manual washing (Roberts & Guariento, 2009).

4. Thermal analysis of BIPV

The average efficiency of the PV modules is 15% which means only 15% of the solar energy is converted to electricity and 85% is converted to heat. Therefore, the performance of the PV module decrease as the temperature of the PV module increases. In polycrystalline silicon PV cells, the efficiency is changed around -0.4% for every one degree of temperature increase. And in amorphous silicon PV cells, the efficiency changes almost -0.2% for each degree of temperature increase.

The difference between the temperature of the PV module and ambient temperature is dependent on the intensity of irradiation, that can be more than 40C degree. So, in the summer season that the ambient temperature is high, the temperature of the PV module reaches 70-75 degrees. Some PV producers determine the nominal operating temperature of PV cells (NOCT). PV cell temperature is specified for irradiation of 800 W/m2 at 20°C ambient temperature and wind velocity of 1m/s (Roberts & Guariento, 2009).

4.1. Temperature effect and ventilation

The temperature of the PV cell is depending on the ability of PV cells to transfer the heat. Freestanding PV arrays would be only 22C warmer than the ambient temperature, but when the backside of the cell is insulated the heat is released only from the front side of the cell and the cell temperature would rise. To increase the heat loss by the cell an air gap should be created between the PV element and the structure of the building where the cell is mounted. This provides airflow on the backside of the cell and allows the cell to cool down by natural convection.

Without ventilation, the temperature of the crystalline silicon roof-mounted PV cell could reach 43°C higher than the ambient temperature, whilst with good ventilation, the cell temperature reaches to at most 29°C higher than the ambient temperature and a large gap would reduce it to 28°C temperature difference.

Vertical facades cells are cooled less properly compare to the rooftop cells. With good ventilation, the cell temperature would reach 35°C higher than the ambient temperature and without ventilation it could reach 55°C higher than the ambient (Roberts & Guariento, 2009).

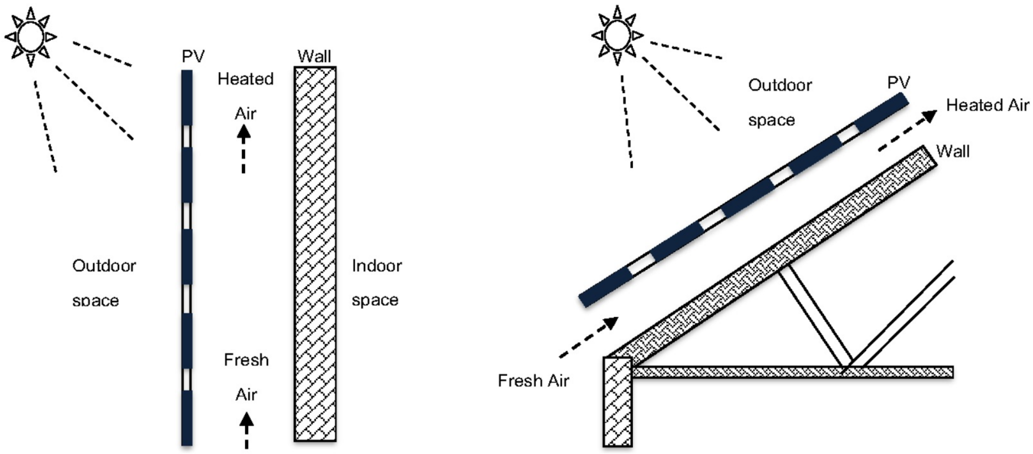


Fig.13 Schematic diagram of the BIPV system investigated, in vertical position (façade installation) and inclined position (roof installation)
Source: Agathokleousa & Kalogiroub, 2016

4.2. Useful output and daily insulation

4.2.1. Daily insolation

The average daily insolation is the key to clarify the useable energy output of the PV system during a year. Daily insolation value is deferent from location to the location regarding the length of days and altitude of the sun. The weather and cloud pattern of the area are other main features to characterize daily insolation. Electricity generation of grid-connected modules is normally assessed during a year hence the annual average of daily insolation must be determined considering the value of every month. Figure14 is the map of worldwide daily insolation zones (for the horizontal surface). Different zones are shown by curves based on capturing climate data over the years (Roberts & Guariento, 2009).

The useful energy output is defined by the average daily insolation and shown in kilowatt hour (kW/h) unite. The annual insolation value will maximize when the recipient surface is tilted around 20 degrees less than the altitude angel and when the north of tropic of cancer is oriented south (in the northern hemisphere). The map in figure 16 shows the average daily solar radiation of the horizontal surface. As the tilt increases the insolation value, there are sort of maps based on the flat surface tilted the south direction at the equal angel to the latitude. Table 6 represents the average daily insolation of a horizontal surface over a typical year.

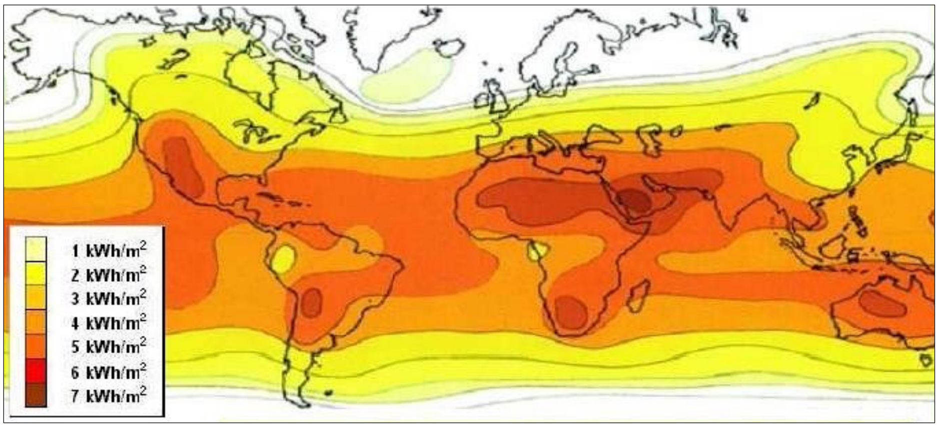


Fig.14 Map of worldwide daily insulation zones
Source: Ismael Ammar, 2015

Table.6 Annual average of daily insolation on a horizontal surface “tilt 0”. (own table)

kWh/(m2.day)	Kwh/(m2xyear)	MJ/(m2xyear)
1	365	1.3
2	730	2.6
3	1095	3.9
4	1460	5.3
5	1825	6.6
6	2190	7.9
7	2555	9.2

To estimate the electrical output over a year the monthly amount of solar radiation of the given location is needed. The following diagram shows the monthly average value for the daily insulation of a northern latitude site. The highest monthly value in July is almost 6kWh/(m2xday) and the lowest in December is 1.2kWh/(m2xday). The annual average is 3.57kWh/(m2xday).

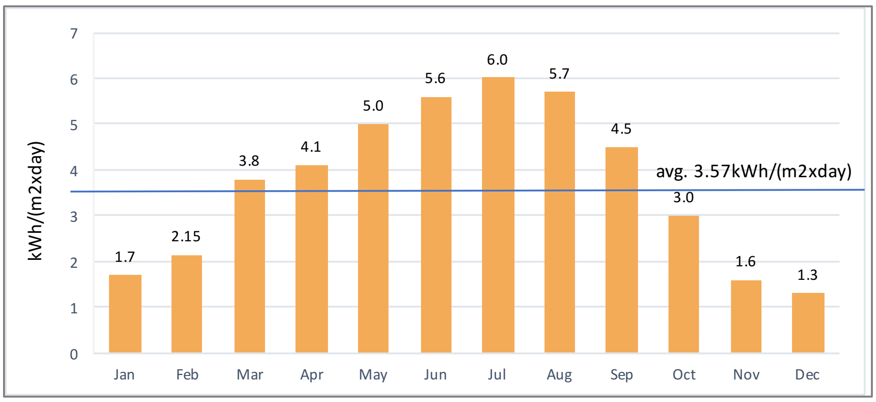


Fig.15 Monthly average of daily insulation of a northern latitude site. (own chart)

4.2.2. Useful output

The main factors which determine the total useful electrical output of a PV installation during a year are:

- *"Annual average daily insulation*
- *Tilt and orientation of the PV array*
- *Whether there will be any overshadowing or partial shading*
- *Extent of solar heating (or ineffectiveness of ventilation cooling)*
- *Efficiency of the balance-of-system components*
- *Efficiency of PV module, as dependant on the type of PV material."* (Roberts & Guariento, 2009: 42)

There are a number of professional PV software(s) to calculate the PV installation output. Here is a simple example of the output calculation;
Data from the site:

- Average daily insulation is 3.6 kWh/m2.day for the horizontal surface. And 4kWh/m2.day at the optimum tilt that increases the output.
- Vertical surface facing south has 74% efficiency compared to the optimum tilt.
- The south face is free shading.
- The heating produced by the PV system reduces 4% of the output.
- Balance of the system losses is 15%.

This will be the estimation of the annual output per kilowatt peak (kWp) of this system: 365 days/y x 4 kWh/m2.day x 74% x 96% x 85% = 881 kWh/y. Then the required area for PV arrangement to generate 881Kwh/y electricity would be 8m2 if the units are monocrystalline silicon with 8m2/kWp. It means each m2 of the PV module generates 110 kWh/y (Roberts & Guariento, 2009).

4.2.3. Specific yield of PV installation

Specific yield is calculated from the values of generation data taken from an existing PV installation in the near location. This value is established from dividing the generated energy by the boilerplate or STC rating given as kWh/kWp.year. Or simply described as "*how much energy (kWh) is produced over one year by a specific quantity of installed PV modules (1kWp)."* (Roberts & Guariento, 2009: 42)

The energy output is a value shown by an electricity meter. In this value losses caused by the balance of the system (BOS) components such as inverters, load matching, and wiring resistance are taken into account. However, there are many other factors involved with this figure such as orientation, weather, latitude, the performance of the installed PV system, type of the PV installation and maintenance of the system. Hence data from similar PV installations with similar conditions is what should be considered to obtain the right comparison regarding the specific yield.

There are commercial PV module technologies available on the market:

"1. Thick crystal products include solar cells made from crystalline silicon either as single or poly-crystalline wafers and deliver about 10-12 watts per ft² of PV array (under full sun).

2. Thin-film products typically incorporate very thin layers of photovoltaic active material placed on a glass superstrate or a metal substrate using vacuum-deposition manufacturing techniques similar to those employed in the coating of architectural glass. Presently, commercial thin-film materials deliver about 4-5 watts per ft² of PV array area (under full sun). Thin-film technologies hold out the promise of lower costs due to much lower requirements for active materials and energy in their production when compared to thick-crystal products." (Steven Strong, 2016: Building Integrated Photovoltaics BIPV)

5. On-site generation and consumption

Grid-connected BIPV systems are designed to generate electricity for the demand of the buildings in which they are mounted. When the demand of the buildings is high, they consume the entire output of the system and when the demand of the buildings is less than the output, the excess electrical output would transfer to the grid. Building consumption by the PV system reduces the consumption from the grid, also minimizes the cost of electricity for the buildings. The switching of electricity transmission between buildings and the grid happens automatically and needs no human interventions.

Commercial buildings are great options for on-site renewable energy generation. Not only they can minimize energy requirements by maintaining efficiency principles but also, they develop energy self-sufficiency of the buildings. Moreover, feeding the excess electricity from these buildings into the grid would provide the companies with kind of a credit account in utility service which reduces their electricity costs. However, developing the local energy generation is worthy in different ways as follows:

Energy cost savings: The cost of onsite electricity generation is less than buying electricity from the utility. Buildings equipped with the PV system can distribute their excess generated electricity to the other buildings in the neighborhoods. Also, the heat gains associated with power generation can be captured and used to avoid or reduce any excess costs regarding space heating. This also defines the energy self-sufficiency (socalgas).

Reliability: Onsite generation provides a dual source of energy. The useful output of the onsite system would moderate the transmission voltage of the grid and when the output of the system is low the power would be available from the grid (socalgas).

Power quality: A better power production can be provided when the onsite system is equipped with a small power storage system. These systems would prevent harmonics, voltage sag and momentary outages and eventually improve power quality (socalgas).

Pollution prevention: Reduction of emission regarding onsite solar power generation improves air quality and human health.
Risk management: Onsite generation would bear the fluctuations in the electricity market caused by the impact of seasonal and daily weather on the cost of electricity (socalgas).

5.1. Micro grids

A micro grid is also known as the local grid consists of energy units (BIPV panels in this case) that provide electricity demand of the building where it’s mounted and is connected to an external power system (utility grid). Micro grids can either be operated as a stand-alone system or be connected to the other micro grids in the neighbourhood areas without any reductions of system performance on providing their own energy demands.

In grid-connected cases, both generation system and the consumer are connected to the utility grid. This would help utility system balancing the loads by feeding the excess energy to the grid during high demand periods, and would provide revenue for the micro grid. Standalone grids may require an energy storage system as an alternative to complete the micro grid system. It means providing batteries on-site to store the excess energy production when the generation is higher than the demand of the building. Batteries supply the building when the demand increases also during the low sunshine hours or when there is no sunshine at all. They can distribute stored energy to other local grids in the neighbourhood as well.

5.2. Smart Grids

The smart grid is a micro grid system equipped with advanced control systems in which the main system components including electricity sources (BIPV panels), energy loads, electricity meters and energy storage systems are in a corporation to be operated and optimized as an integrated system. The advance control system helps to reduce energy consumption while the micro grid stability is improving. This needs a concrete plan designed by expertise in building designs, power generation, and storage systems.

5.3. Energy storage system (stand-alone systems)

Energy storage reduces the energy cost and provides free and sustainable energy especially at nights, during low sunshine hours or no sunshine at all. Solar battery (storage system) is an important part of self-sufficiency, as with solar battery no electricity is feeding into the grid and there is no need to buy electricity from the grid, therefore, the electricity bill will remarkably increase (solarwatt).

Photovoltaic systems without storage provide electricity to be used immediately. This could be insufficient since solar energy is mainly generated during sunshine hours. With a battery storage system, the excess produced energy during sunshine hours can be stored to be used when there is an actual demand. Here are the benefits of photovoltaic systems with battery storage:

- Making it feasible to use the excess solar power produced during the day when it is actually needed.
- Permanently reducing the electricity bills
- Individually contributing to a sustainable future
- Optimizing the self-consumption of the PV systems
- Providing independency from large energy suppliers (solarwatt)

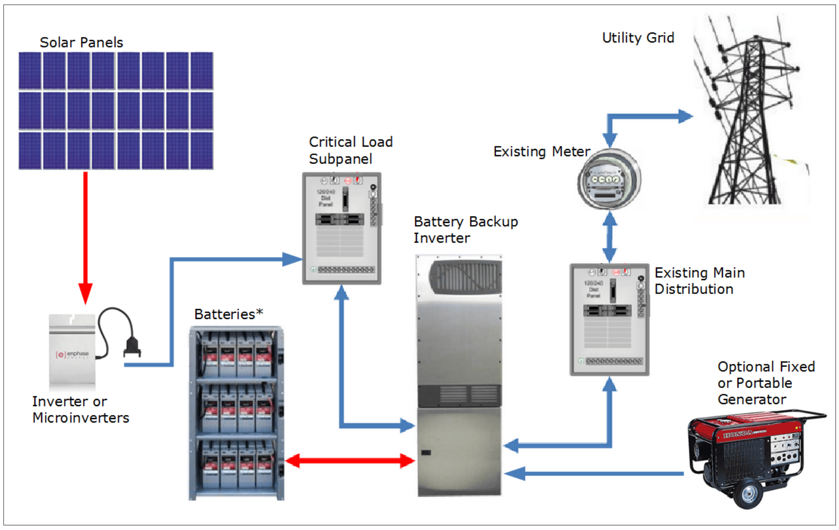


Fig.16 Solar backup battery storage schematic
Source: Florida Solar Design Group, 2015

5.3.1. Solar batteries

solar batteries make the solar energy available when there is electricity demand, usually during evenings and nights. The function of this system is simple, as the generated energy by the PV system is initially used for self-consumption immediately when there is demand, and the excess generated power is stored in the battery. Having the batteries fully charged will dramatically speed up the aging process of them (figure 17), therefore when the self-demand is low the most part of generated power is transferred to the grid to prevent the battery from being fully loaded. This is called intelligent charging.

If the demand is higher than the produced power the stored energy in the partly charged battery is available to consume the building. But if the battery is fully discharged then the power will be available from the grid. With this principle, the whole demand of the building will be covered during days and nights.

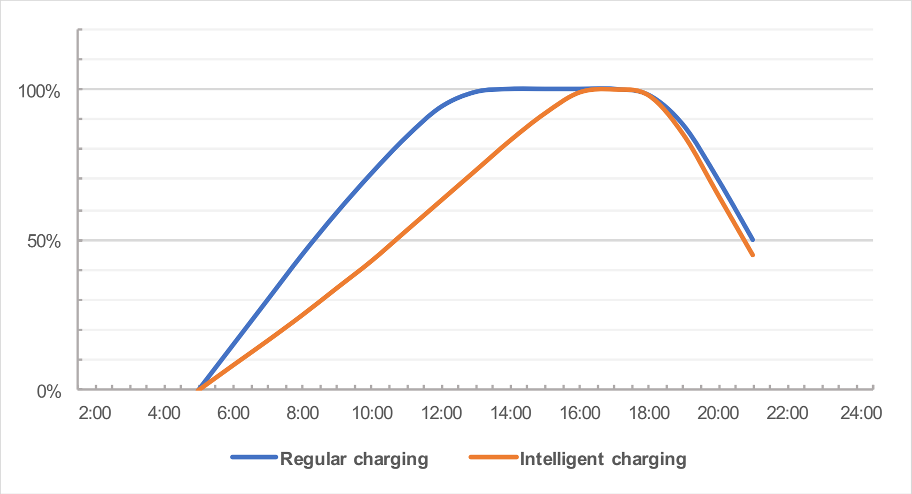


Fig.17 Regular battery churching vs. Intelligent charging during hours of a day (own graph)

5.3.2. Storage capacity

The capacity of the storage system depends on the demand of the building. Generally, the storage system should be large enough to supply the building at no sunshine hours. Inappropriate calculation of the needed capacity would result in extra cost if the storage capacity is too small to cover the demand. Also, if the storage capacity is too larger than required, unneeded power storage would happen which reduces the battery's service life (solarwatt).

5.3.3. Depth of discharge (DOD)

To prevent storage system damages, most of the battery systems need a residual charge. DOD or the depth of charge indicates what amount of energy can be taken out from the device and it's shown in percentage. The normal depth of discharge lies between 50% for lead batteries and up to 100% for lithium-ion batteries (solarwatt).

5.3.4. Efficiency and lifetime of the storage system

Losses usually happen during the conversion as a part of the energy is converted into the heat. The total efficiency of the system indicates what percentage of the stored energy can actually be used which is usually somewhere between 70% to 90%. However, the total efficiency of the system is not dependent on only the battery but on the whole storage system components from the roof to the sockets. Total efficiency is lower than the efficiency of the battery because of the conversion losses. To overcome the losses issue, the first DC to AC conversion could be skipped and the solar power can directly flow into the battery. This way the losses would be reduced to a very small portion and the DC current is only converted to AC when it's feeding into the building. This could increase the efficiency of the system by more than 90%. The lifetime of a storage system depends on the model and the manufacturer and varies between 5 to 15 years (solarwatt).

5.3.5. Lead and lithium-ion batteries

Lead-acid batteries were more popular in the past, but lithium-ion batteries have become increasingly more and more favorable than the lead-acid batteries due to their remarkable advantages. They have come to be regarded as the standard in photovoltaics in recent years.

Features of lithium-ion batteries vs. lead batteries;

- The lifetime of lithium-ion batteries is expected to be 15 years, whilst the maximum lifetime of lead batteries is 5 to 10 years.
- Lithium-ion batteries discharge the entire stored power but lead-acid batteries can only discharge half of the stored power because further discharge would decrease their service lifespan.
- Lead batteries need to be only installed in a ventilated room because they emit gases. This is not necessary for the lithium-ion batteries.
- The efficiency rate of lithium-ion batteries is almost 90% but for lead batteries, it's only 70% at most. This issue increases the size of the PV systems with lead batteries and creates unnecessary costs (solarwatt).

Figure 18 shows the global development of storage technology as follows:

- The annual cost reduction of battery systems is reported 9% to 16% (equivalent to the current market development in Germany)
- The annual cost reduction for battery was reported 11% (equivalent to IRENA 2015)

− The primitive annual cost reduction of converters has been around 20% between 2017 and 2020 (Dr. Rezania, 2018)

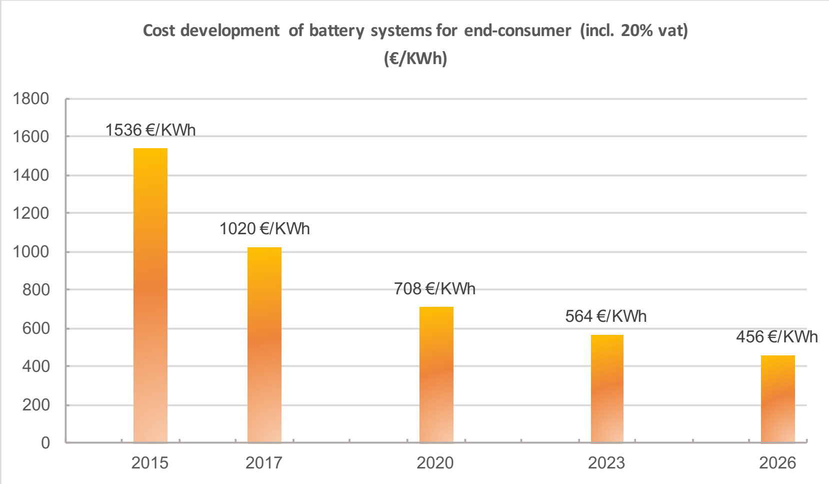


Fig.18 Global development of storage technology
Values from: Dr. Rezania, 2018

5.3.6. Battery integration into existing PV system

Battery integration to a PV system which is already existed is not easy and entails technical changes such as inverter replacement. On the other hand, the huge size of the batteries and their heavyweight make them difficult to install and set to the right work condition when there is space limitation for installation. However, the new generation of batteries are light weighted and compact dimensions therefore are easy to install. The principle is that the battery is installed on the DC side of the inverter to store the DC current coming from PV modules. When the electricity is feeding into the main network the DC to AC conversion happens. As mentioned before this would reduce the losses and increase the total efficiency of the system. of course, this type of integrations needs to be done by experts.

6. Energy meets Architecture

The main concept of designing PV modules is to generate electricity from solar power as they are installed inside the site of a plant. But when it comes to building integration, PV modules not only generate power also have to play the role of elements of the building such as wall, window or roof cladding. The building envelope is the area where PV modules could be mounted. The building envelope is the interface between the indoor environment of the building and the outdoor environment hence, the structure of the building envelope should technically prevent unnecessary heating and cooling transfers (thermal protection) in order to obtain the best performance of the ventilation system. Also, it needs to be weathertight to provide a proper defence against air and water transfers inside the indoor environment (Roberts & Guariento, 2009).

PV integration to the building is so much influenced by features of the design and also elements of the building envelope such as size, material, surface-finishes - including the main segments and subdivisions. Therefore, to attain the energy production requirements the PV integration must be considered and discussed from the start of the design of the building and trough the construction principles.

6.1. Architectural design for energy efficiency

Poor architectural design would result in bad energy performance. This means if the climate conditions of the location are not considered within the architectural design, then the energy consumption of the building would increase. As the energy costs are increasing and the subsidies for energy are decreasing, the energy-saving methods in buildings are becoming essential.

Using expensive building insulation materials to save energy is not a very interesting method since the high cost of these materials would increase the whole building costs but using cost natural energy-saving methods would naturally reduce the energy consumption of the building and would rarely increase the building costs. These methods are carried out within the intelligent architectural designs and don’t require any special building materials.

According to the IEA report 2016, the global energy consumption of the buildings can grow to 50% by 2050 without energy-efficiency practices and yet 80% of the energy efficiency potential of the buildings is unused. This report emphasizes on developing energy efficient techniques in the building sector.

6.2. Energy efficiency principles (reduce before produce)

Generally, the building loads are divided into four categories of lighting, appliances and equipment, heating and cooling and domestic hot water. Regardless of the energy source type, losses would happen due to the low efficiency of the energy system. Some portion of the building's requirements could be provided without using power (figure19) such as natural ventilation and solar heat gains. And during the daytime that daylighting could be achieved via the windows. This method is called the passive system (Krarti, 2018). Passive systems are described in chapter 6.3.

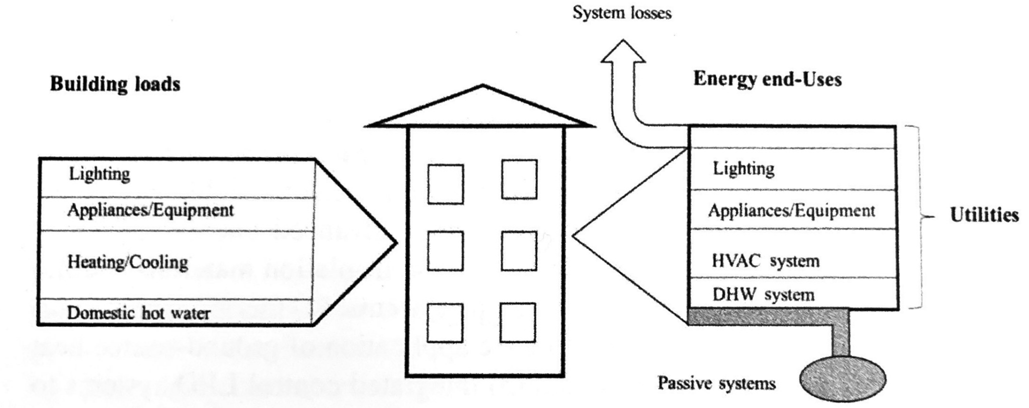


Fig.19 Building loads and energy consumption end-uses for conventionally designed and operated buildings (Source: Moncef Krarti, 2018)

Given the fact that only when the buildings' loads and energy uses are minimized they are considered energy-efficient, brand-new constructions should follow some design regulations to make sure they are provided with the standard required level of energy efficiency.

The design regulations are:

- The insulation standards.
- Air leakage level of the floors, walls, roofs and windows.
- Standards for lighting fixtures.
- The efficiency level of the office equipment and appliances (especially commercial and educational buildings).
- Domestic hot water system (DHW) as well as the heating, ventilation and air conditioning system (HVAC).

Moreover, building rating labels which are based on the energy certification of the building motivate the designers to consider renewable energy system providing energy demands of the buildings. The idea of the net-zero energy building (NZEB) has shaped and become popular over the last decade. The concept of a typical NZEB is, the energy produced by the roof-mounted PV systems is directly used for the energy demands of the building or is being transferred to the utility grid (Krarti, 2018). ZNE system is described in chapter 6.3.1.

However, as mentioned before the first step towards energy-efficient buildings is reducing the building's loads, which must be carried out while maintaining the acceptable thermal comfort level. This means the thermal comfort should be provided in every climate condition and should not be slipped by reducing energy consumption. The thermal comfort level (occupants' comfort level) and the quality of air together determine the indoor environment quality (IEQ). Besides selecting a proper energy system to minimize energy consumption, optimization of the system operation should be also considered.

Here are the strategies to decrease the loads and increase energy efficiency of the new and existing buildings;

- Space cooling could be reduced by reducing the solar gains and the thermal mass of the building which reduces the internal gains as a whole.
- Natural ventilation or mixed-mode ventilation could reduce the energy requirements for ventilation.
- The energy need for lighting could be decreased by installing high-performance units and considering integrated controls.
- Energy consumption for hot water could be decreased by setting the heating temperature at proper degrees and minimizing the losses of distribution.
- Energy consumption of office equipment and appliances could be reduced by selecting energy-efficient systems along with smart control of their energy use (Krarti, 2018).

6.3. Passive systems

Passive systems maximize the natural energy gains for buildings. features of climate conditions and surrounding elements in the area should be all considered regarding the system function as the ambient air, sun and the ground medium would provide heating, cooling, and ventilation without energy or with low energy consumption. In a hot climate, the passive system provides minimum solar heat gains and maximum natural lighting (by optimizing the size of the windows and by using shading devices). And in cold climates, the system provides maximum solar heat gains and maximum natural lighting.

The function of the passive system is that during cold seasons when the temperature of the outdoor area is below the temperature of comfort level, the stored heat gains of the day are released into the indoor area during the night. An additional low energy system like a ground source heat pump is considered to provide the remaining demand. This way the power consumption for space heating will be decreased. And in warm days, natural ventilation would chill down the thermal mass of the building (floors and walls). Then the demand for space cooling would be minimized.

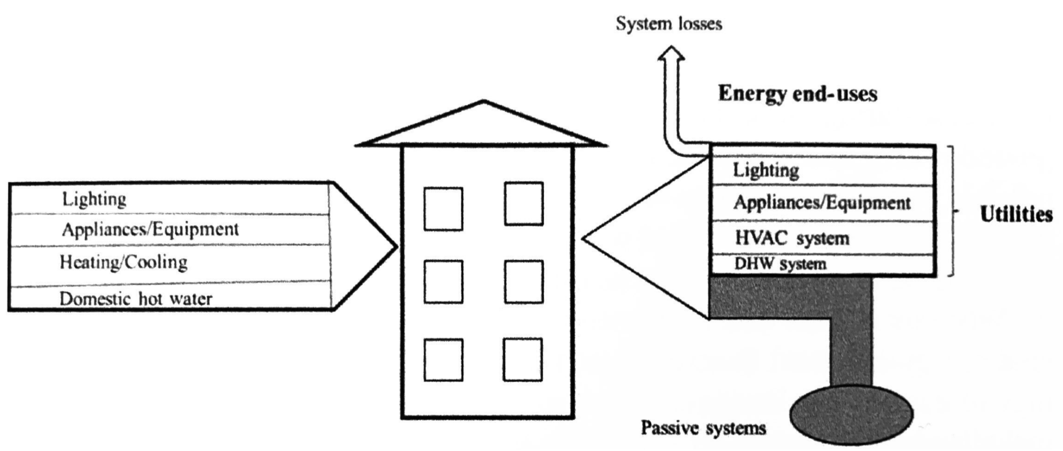


Fig.20 Building loads and energy consumption end-uses for energy efficient buildings
Source: Moncef Krarti, 2018

6.3.1. Zero net energy buildings

Toward improving the energy performance of buildings some concepts like net aero energy building have shaped. these concepts initially were used as traditional methods to design new buildings with high energy performance, but recently they are applied to the existing buildings as well to identify and select the most effective factors of the energy performance of existing buildings. Achievements of these methods are used to develop a program on improving the energy performance of existing buildings by minimizing energy costs and maximizing energy savings. Such an optimization program requires detailed analysis and special tools (Krarti, 2018).

The nearly zero-energy system is identified as an on-site generating system. In this system, the source energy (solar in this case) responds to the on-site generation plus the energy used for generating, transmitting and distributing the site energy production. Not only the source energy provides proper data to analyze the function of NZE buildings, it also clarifies the impacts of such energy production on the environment and society.

According to the analysis, NZE buildings produce as much energy as they consume on-site annually. Particularly NZE buildings equipped with PV systems use grid energy as a backup system similar to battery storage to decrease their generation capacity (Krarti,2018).

Figure 21 shows the concept of zero-net energy building and energy balance between delivered energy to the building and delivered energy to the grid considering onsite generation and the building need.

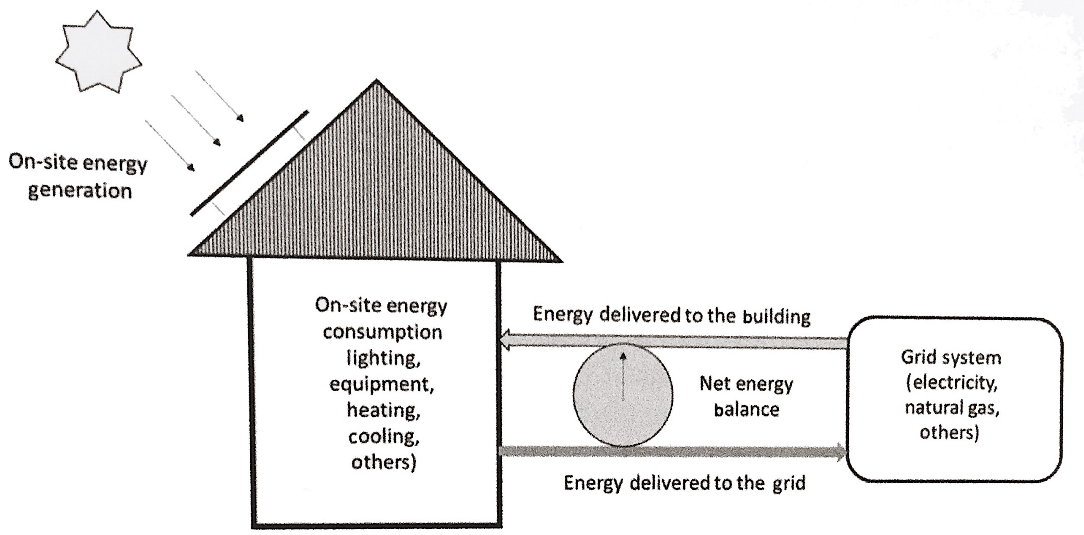


Fig.21 concept of zero net energy buildings (Source: Moncef Krarti, 2018)

6.3.2. Positive energy buildings and principles

The term positive energy building refers to the buildings that produce more energy from renewable sources than they consume to achieve appropriate thermal comfort levels. Following principles must be followed to identify positive energy buildings:

- The energy consumed by the building(s) must be produced on-site which means the energy source or sources are in the site of the buildings or are mounted to the buildings. Also, there must be reliable documents show that this system will maintain generating during the lifespan of the buildings or at least 30 years.
- The produced energy from renewable energy sources should at least supply the demands of the buildings including lighting, heating, cooling, domestic hot water, ventilation, dehumidification and elevators systems in large buildings.
- Appropriate comfort levels must be achieved out of creating a harmony between bioclimatic design principles and integration of renewable energy sources.
- To ensure the building adaptation to the climate, the energy production and consumption of the buildings must be balanced over the year. This also clarifies the seasonal difference in energy consumption of buildings (Global Buildings Performance Network).

Apart from these principles, to be categorized as positive-energy buildings several criteria must be met based on comprehensive design principles. (More information on Global Buildings Performance Network).

Figures 22 and 23 show how the energy balances between demand and supply change based on the application of energy efficiency and renewable energy measures in case (A) ZNE building and case (B) Positive energy building.

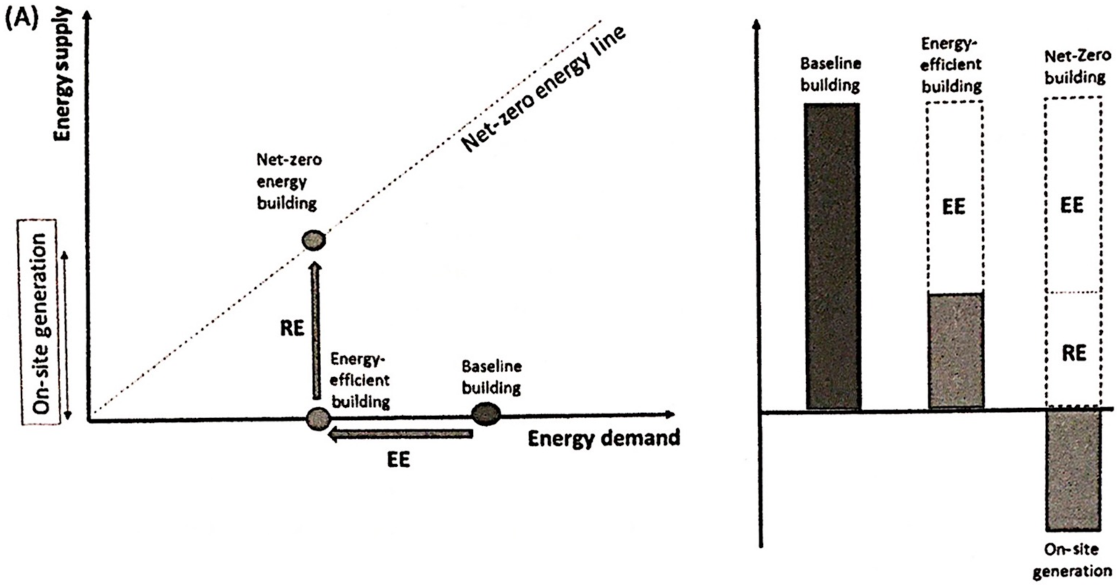


Fig.22 Balances between energy demand and supply. (A) Zero net energy buildings
Source: Moncef Krarti, 2018

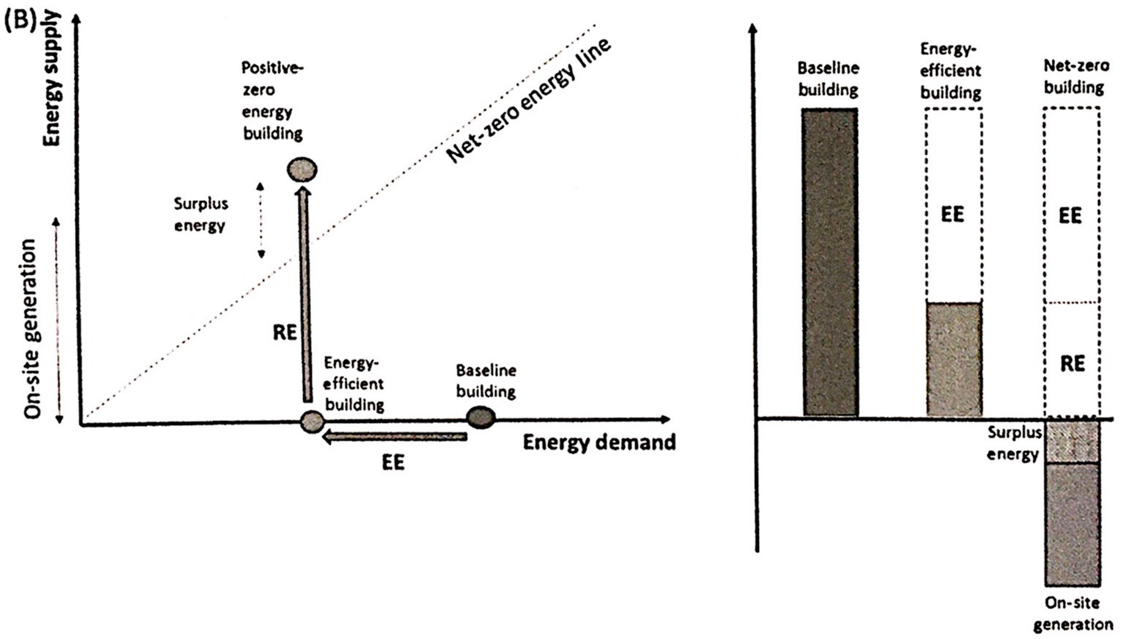


Fig.23 Balances between energy demand and supply. (B) Positive energy buildings
Source: Moncef Krarti, 2018

6.4. Indoor environment quality and controlled ventilation systems

6.4.1. Natural ventilation

One of the main factors regarding improving the energy performance of buildings is the natural ventilation technique. This technique is based on two natural forces, the wind flow and the buoyancy forces that occur inside the building due to the temperature differences. Although natural ventilation is an old technology, it could significantly improve the energy performance of the building. As the cooling potential of the ambient air is used to improve the indoor thermal comfort the need for mechanical air conditioning systems would be decreased. Therefore, buildings can be designed the way to benefit from these two natural forces to reduce energy usage and decrease energy costs (Krarti,2018).

Natural ventilation directly impacts on the thermal comfort level of indoor area and thermal comfort level impacts on the occupants' satisfaction with their working environment. Therefore, job satisfaction and productivity of occupants would increase by increasing the comfort level of the working environment.

However, natural ventilation technology works better in areas with mild summers like in Europe. Studies show that in extreme climates such as warm weather of Tehran in Iran and warm and humid area of Melbourne in Australia using natural ventilation as the only technology is not sufficient to reach the acceptable level of the thermal comfort. Hence, a supplementary mechanical force would be required to complete the ventilation system (hybrid ventilation system). With hybrid ventilation system buildings would maintain the desired thermal comfort level during extreme weather conditions and the same time making benefit from natural ventilation. A better understanding of the Hybrid Ventilation system may reach through this definition: "*using natural forces when they are sufficient and mechanical assistance when necessary."* (Krati, 2018: 322)

Providing buildings with free natural cooling and ventilation would lead to optimizing the usage of energy for HVAC system. Figure 24 shows the schematic of natural ventilation in a high-rise office building.

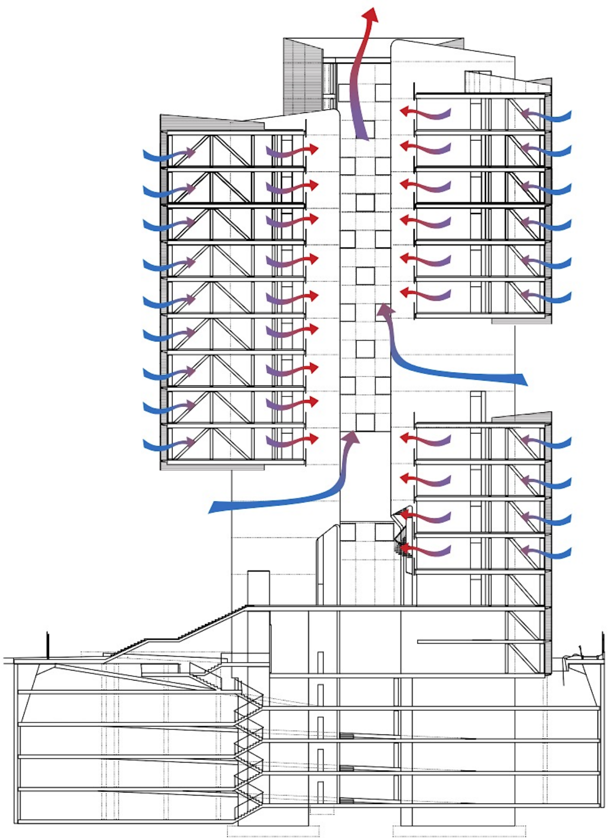


Fig.24 Natural ventilation in a high-rise office building
Source: Wood, A & Salib, 2013

6.4.2. Indoor air quality and comfort level

Evaluation of two factors of indoor air quality and comfort level is required to determine the indoor climate condition. Given that a poor indoor climate would result in a lack of concentration, tiredness, and even illnesses, improving the indoor climate would overcome these issues and increase the performance of building occupants. Following parameters would determine the quality of the indoor climate:

Carbon dioxide (CO2) concentration:

Considering that the occupants can cause emissions, hence the CO_2 concentration should never reach higher than 1000 ppm to minimize the risk of tiredness and illnesses (testo 400).

Turbulence degree:

Another factor that directly affects the thermal indoor comfort level is the air velocity. The degree of air turbulence is a percentage that indicates fluctuations of the air velocity and intensity of the airflow through the indoor area. The air temperature and turbulence degree have a direct relation.

Temperature and humidity:

Temperature and relative air humidity are the basis of the thermal comfort level. These two parameters need to be considered for choosing proper heating and ventilation systems. For most of the building, the best humidity level is 40% - 45%. Any level below 30% is recognized too low and above 50% is too high (American industrial hygiene association).

Radiation heat:

Generally, if the workplace is exposed to heat people would struggle to handle the workloads. Wet Bulb Globe Temperature (WBGT) is the index used to distinguish workplaces that are affected by thermal radiations. This index also defines the maximum allowed exposure time.

Thermal comfort level (PMV/PPD):

The thermal comfort level is defined by some of the prior parameters including indoor air temperature, air velocity, radiation temperature and relevant humidity of the indoor air. However, these parameters may affect differently the comfortable feeling of people since the feeling of comfort is varied to individuals based on their activities and their clothing (testo 400).

"*all of the parameters are combined in the PMV/PPD measurement (Predicted Mean Vote/Predicted Percentage Dissatisfied). The PMV index predicts the average climate assessment value of a large group of people. The PPD Index provides a quantitative prediction of the number of people that will be dissatisfied with a certain ambient atmosphere."* (ISO 7730)

Light:
Sufficient light is an essential requirement in every workspace. It's not only necessary for job performance but also prevents premature tiredness and helps to maintain concentration.

Sound:
This parameter is considerable regarding workplaces. The noise level would affect the work performance of staff. It has been proved that noise pollution would influence the indoor comfort level and therefore would reduce the efficiency of the staff at work.

6.5. Design for optimal thermal comfort

Regarding the building design, there is no thermal comfort global range or standard since comfort feeling is different from place to place and from person to person. For instance, the thermal comfort level in a gym is different from an office building or a clinical center. Also, people from different regions have different expectations for desirable indoor thermal comfort levels. If *"we were to briefly define 'thermal comfort', it is the creation of building systems that are adapted to the local environment and functions of the space, cooperatively."* (Stouhi 2019, How to design for optimal comfort and why it matters)

Building's envelope is the first key element regarding indoor thermal comfort. The building envelope is the separator between the outdoor environment and the indoor ambiance of the building. So, with a proper design for building envelope, the indoor air quality will improve naturally and eventually the need for using mechanical ventilation systems will be reduced. These parameters should be considered for designing an efficient building envelope: solar gains, insulation, thermal inertia, and air ventilation (figure 25 & 26).

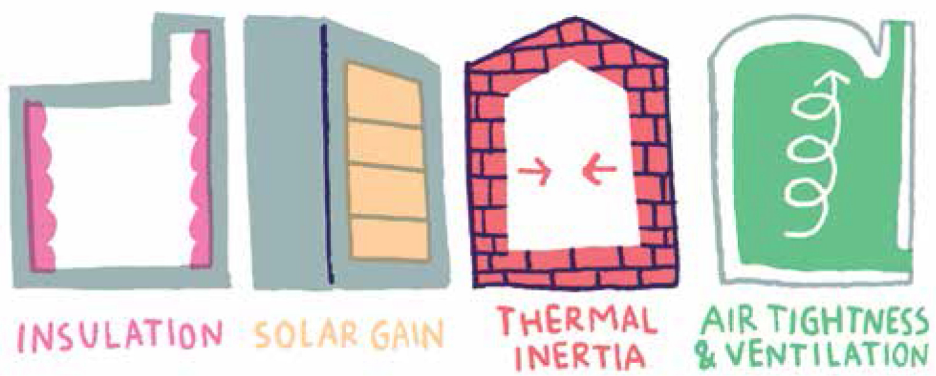


Fig.25 The building envelope can greatly affect the interior thermal environment through the management of these parameters. Source: Stouhi, 2019

Solar gains: Solar gains should be considered through the building design and orientation of the building. Parameters such as, the ratio between glazed and opaque areas, heat reflection of the building's components, insolation level of the building as well as the shading elements which are existing or will be existed around the building need to be controlled regarding this matter (Stouhi 2019).

Insulation: High insolation properties need to be considered in both glazed and opaque areas to reduce heat gains during warm seasons and conserve heat during cold seasons.

Thermal inertia: Thermal inertia is a parameter that defines how slowly the temperature of the building reaches the temperature of the outdoor environment. This parameter is deponent on the materials of the building structure. In other words, the thermal reaction of the materials is used for indoor cooling and heating. So, in hot climates materials with high thermal inertia must be used to maintain ambient cooling as long as possible. Stone and brick are known as high thermal materials and are the best options for this purpose. In contrast, in cold regions materials with low thermal inertia should be used to boost indoor heating. Wood is known as a popular material with low thermal inertia and is widely used in cold regions (Stouhi 2019).

Air ventilation: Fresh air is essential for a healthy indoor area. Natural or mechanical ventilation provides air exchanges.

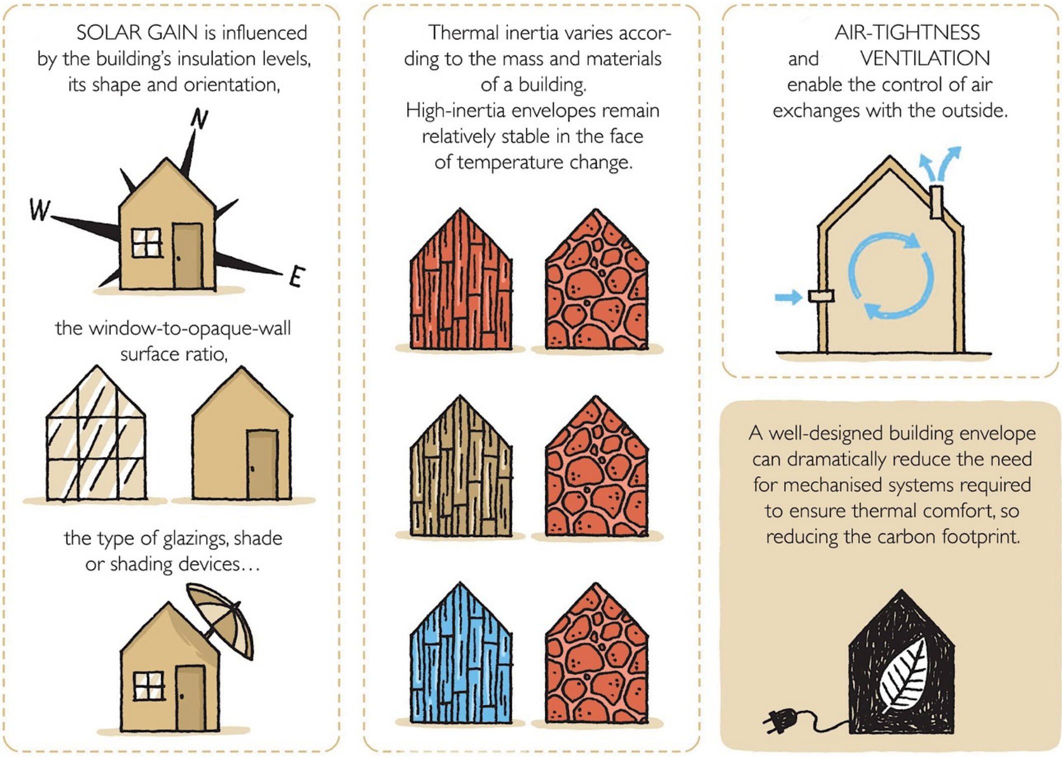


Fig.26 The effective parameters for designing an efficient building envelope
Source: Stouhi, 2019

Figure 27 is an ideal example of a high-energy performance building. The section shows how a self-sufficient building performs by considering renewable sources of energy along with the optimal construction options that provide the building with high energy performance. As shown in figure 28, the rooftop area is covered with both solar collectors and solar PV panels and the roof surface is 19 degrees tilted (reminding: the annual insulation value will maximize when the surface of the module is tilted around 20 degrees less than the altitude angel and when the north of tropic of cancer is oriented south in the northern hemisphere). Also, the atrium area in the center of the building is an excellent idea to create an additional source of daylight for the indoor space.

Proper insulation and application of the right building mass improve the thermal comfort of the building. The passive exterior sun shading located on the southeast of the building improves the thermal balance between the indoor area and the outdoor environment.

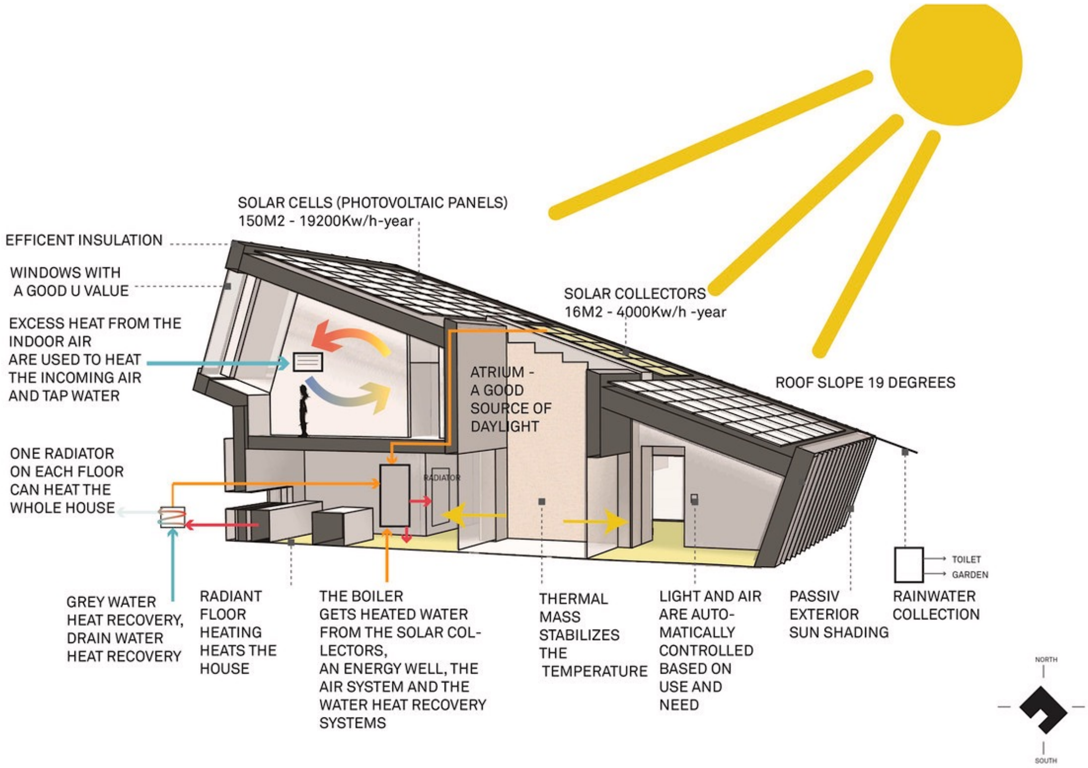


Fig.27 Section of a high-energy performance building
Source: Stouhi, 2019 (Diagram by Snøhetta)

6.6. Thermally activated building system

The main aim of the thermally activated building system (TABS) is for cooling multi-story buildings but this technique is also used for heating. The function of the TABS system is by activating the building mass to obtain direct cooling and heating effects. Not only the TABS provide an energy-efficient system, but it also performs as a cost-effective technology considering that having the building mass activated would minimize the peak load and shift a part of the cooling load of the building to the outside of the building's occupation time. Moreover, this technique could decrease the total energy consumptions of the building by almost 13% (Olesen, 2012).

TABS Concept:

TABS technique uses the existing thermal capacity of the building mass to provide cooling. As the building mass is activated, the heating and cooling characteristics of the building mass are engaged to simplify the temperature control of the building. TABS functions as a radiant cooling system. Water pipes are placed in the concrete core of the floors, walls, and ceilings to have the water flow influencing the temperature of the concrete and create the energy transfer (figure 28). This is called the radiant cooling system. The high thermal inertia of the concrete slab plays a key role in the system performance by minimizing the cooling requirement of the building. This would let the structure of the building to cool down when the building is unoccupied during the night hours at lower energy costs (Olesen, 2102).

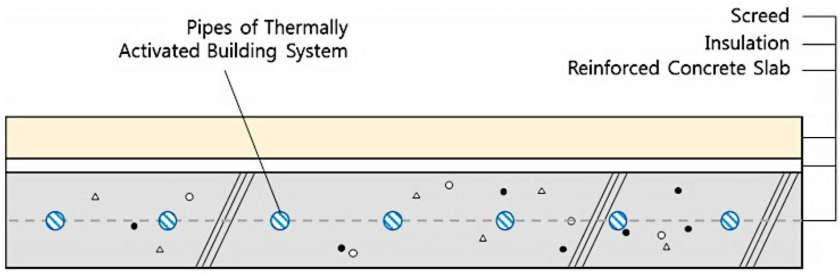


Fig.28 Section view of the thermally activated building system (TABS)
Source: Chung, W.J. et.al, 2017

Installations:

TABS installation is onsite as a part of the building's construction. The pipes are installed inside the concrete slabs between the upper and lower reinforcement. Using prefabricated concrete modules would speed up the installation process. However, the pressure test of the pipes is mandatory before and after the concrete pouring.

Cooling Source (heat pump):

Heat pumps have high efficiency in TABS systems since a thermally activated building system performs as a high-temperature cooling system and a low-temperature heating system. The temperature of the ground is usually 10°C -14°C hence without using a heat pump water can be directly transferred to the building by a heat exchanger at the temperature of 18C-20C to provide cooling inside the building (Olesen, 2102)

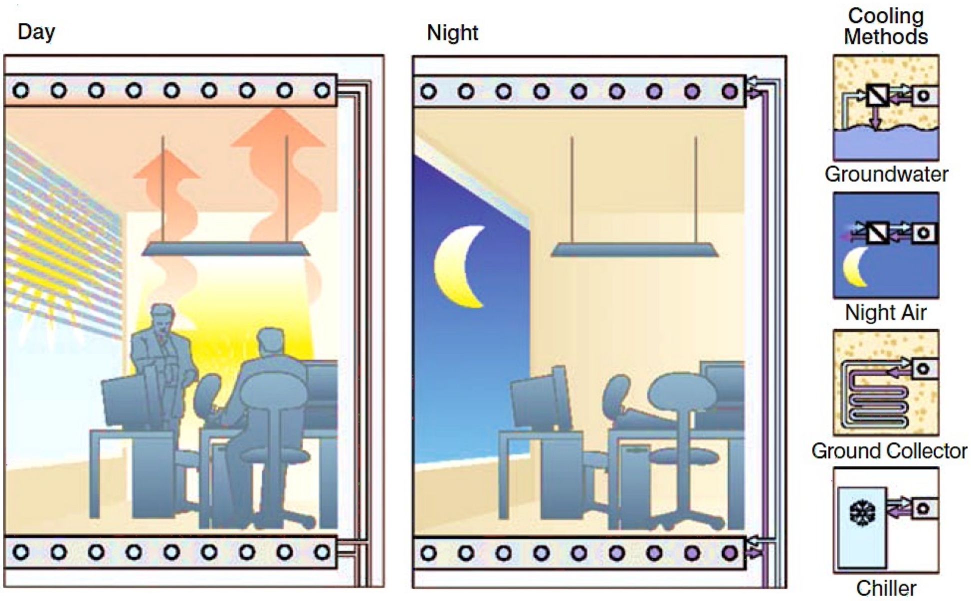


Fig.29 Concept of operation of thermos active building system (Source: Olesen, 2012)

TABS system creates a balance of building loads, and a mechanical ventilation system manages the hidden loads of the building. The high temperature of return water (22°*C to 24°C)* increases the efficiency of the chiller with a high evaporator temperature while the dew point is reduced to avoid the condensation in the space. (Olesen 2012)

Applications:

Thermally activated system is often considered for multi-storey constructions like hospitals, commercial buildings, museums, etc.

6.7. Thermal comfort in future (sustainable design)

The natural environment is affected by global warming and climate change in many ways. Winters are getting shorter and springs are arriving earlier, which means the number of freezing days is decreasing every year. Dealing with extreme climate conditions is enabled through traditional sustainable architectural planning. However, as the cold climates are getting warmer and hot climates are getting harsher, providing thermal comfort is requiring more technical effort.

Moreover, the desired thermal comfort level has been changed during the past two decades due to the changes in lifestyles and human activities. Therefore, architectural techniques need to become more local and livable and mechanical conditioning systems need to be developed further to provide sustainable thermal comfort.

7. Design of BIPV system

BIPV system must be carefully selected and specified considering the building's use and electrical loads of the building. The life cycle costs of the BIPV system besides other relevant costs or issues of the system in the future should be taken into account in the designing process. Also, the principles of construction must be entirely followed. Here are the steps of the designing process of a BIPV system:

Careful design of the adequate energy system:

The adequate energy system is essential to have useful energy production that along with the reduction of the energy requirements will lead to saving energy costs in the long term.

Utility interactive PV system or stand-alone system:

BIPV systems are mostly grid-connected systems, having the grid as a backup or storage. The size of grid-connected PV systems must be adequate for the needs of the building. However, in these types of PV systems, the invertor must be chosen by considering the utility requirements.

Stand-alone PV systems, including storage, must be responding to the peak demand of the building. However, the battery system should never be oversized, hence, for occasional peak loads, one generator is usually considered as the backup. This type of PV system is called PV-genset hybrid (Strong, 2016).

Shift the peak:

This is a remarkable issue when the output of the system is not sufficient to respond to peak loads of the building and the building needs to be supplied by the utility grid at peak loads. This would increase the power expenses, so the alternative technique is to have the system operated as an uninterruptible power system (Strong, 2016).

Appropriate ventilation:

As discussed before (in chapter 4.1) temperature gains would reduce the efficiency of the PV arrays. This issue mainly affects the performance of crystalline silicon PV cells. To increase the efficiency of the cells the airflow should be provided throughout the space between the module and the building surface to reduce the heat.

Design of hybrid PV solar thermal systems (optional):

An option to improve the system efficiency is capturing the heat produced by solar panels to be filtered and used for pre-heating the incoming ventilation air.

PV modules into shading elements:

PV arrays can provide appropriate solar shading. If the sunshades are part of the integrated system design, then the capacity of the chiller could be smaller and ambiance cooling distribution could be minimized or even removed (Strong, 2016).

Create daylighting / design skylight PV system:

Designers can consider semitransparent thin-film or crystalline modules to create daylighting features in roof and façade or even create a skylight PV system. This is done by making custom-spaced cells placed between two glass layers of PV modules. Also, PV panels decrease the undesirable cooling force and the glare produced by glass elements (Strong,2016).

Local climate conditions:

Local climate conditions and the existing elements nearby the PV arrays could impact the system output. The output of the system would increase in cold clear days and would decrease in hot cloudy days. Wind loads, rain and snowfalls must be considered regarding PV arrangement. When hen the PV arrays are covered with a reflecting layer such as snow, the output of the system would decrease. Tilted arrays would perfuse the snow loads. In case the PV units are mounted in a dusty dry area or they are tarnished by air pollution, regular washing is necessary to minimize the losses of efficiency (Strong, 2016).

Orientation and unshaded area:

PV panels must receive maximum sunlight and not be shaded by any elements such as neighborhood buildings or trees. Shading on PV arrays drastically impact on the output of the system.

Array orientation:

Tilted PV array is a popular array since it produces 50% - 70% more energy than vertical facade array and provides the system with great annual output.

Connection principles (inverters):

The output of PV modules is DC and this current turn into AC through an electrical interface which is called an inverter. Usually, one inverter is shared a series of connected modules (central inverter). String investors are used for the string of modules and module inverters are suitable for individual modules. In case the PV system is including of sub-array zones and different orientations and tilts more than one inverter would be required. This would be the same for the PV systems consisting of partially shaded modules.

String inverters:

To provide a higher voltage, a series of PV modules could be arranged and connected to one inverter to shape a string. This would minimize the size of the wiring works. Figure 30 shows a series connection of the PV module to one inverter. Through each module of the string, the same amount of electric current is passing. This keeps the size of the wiring part small cause the current never increases (Roberts & Guariento, 2009).

Parallel connection is an alternative connecting pattern in which all PV modules share a relatively low and fixed voltage but the output will have a higher current at the inverter since by adding each panel to the PV array the thickness of the conductors would increase (figure 31).

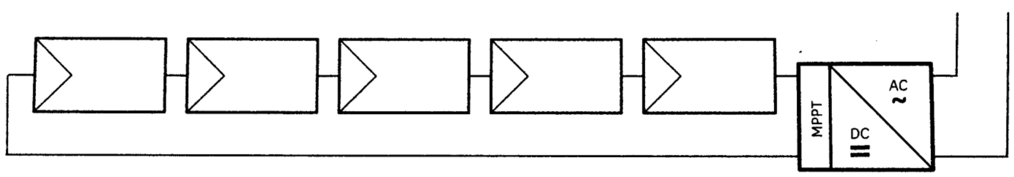


Fig.30 Series connection of PV modules to an inverter
Source: Roberts & Guariento, 2009

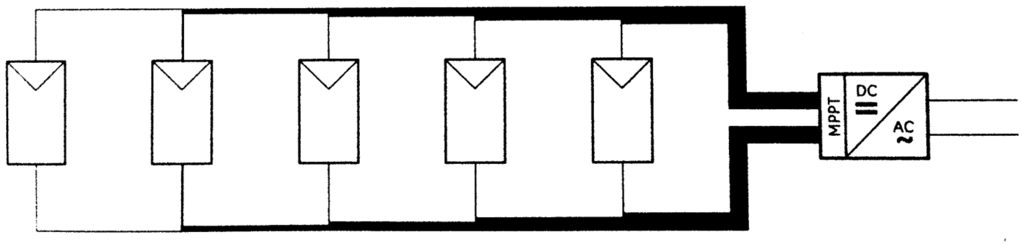


Fig.31 Parallel connection of PV module to an inverter
Source: Roberts & Guariento, 2009

Maximum power point tracker (MPPT):

Irradiance of the sun is changing every moment whilst the inverters should be adjusted to a specified yield of PV modules. This adjustment is carried out by the maximum power point tracker (MPPT) to keep the system at the maximum performance (Roberts & Guariento, 2009).

Other parameters regarding the optimal design of the BIPV system are, reduction of the building envelope, reduction of peak loads and using natural daylighting. Every step of the project including the design, installation, and maintenance must be done by experienced PV experts.

PV units can give different appearances to the building envelope as they can be combined with building materials for instance semi-transparent crystalline cells provide diffusion and natural lighting.

7.1. Orientation and tilt

Orientation and tilt of the building surfaces which receive the sun radiances are the basis of PV system design. Global irradiance is the collection of direct and diffuse irradiance. Direct irradiance is dependent on the position of the sun, angels of sunlight and wavelength during the day and the year. Diffuse irradiance is the radiation coming from the sky, clouds and haze.

Daily insolation is the useful energy output of a PV system. The annual insolation value will maximize when the surface of the PV module is tilted around 20 degrees less than the altitude angel and when the north of tropic of cancer is oriented south (in the northern hemisphere). This angel is due to the peak daily insulation in summer days when the position of the sun is higher than the latitude of the location, hence orienting the PV panels to the summer irradiation will increase the annual output of the system (figure 32).

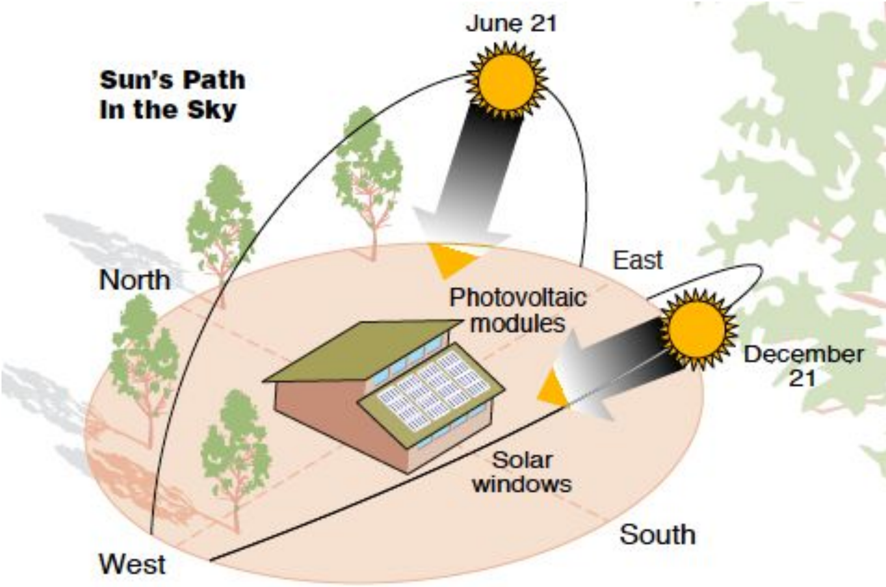


Fig.32 The sun's path on the winter and summer solstices, Courtesy of DOE
Source: Green Passive Solar Magazine, 2013

7.1.1. Optimal orientation and tilt angel for PV systems

PV modules can be mounted in different tilts and orientations yet the optimum orientation and tilt to collect the maximum irradiance are determined from values of the global insulation chart. This chart shows the irradiance values of the given location over a year. The values of the global insolation chart (tilt, orientation, and annual output) would be put on each face of the building to find the optimum orientation and tilt for PV installation. The optimum PV orientation is "true south" and between southeast and southwest, any orientation is possible (Roberts & Gueriento, 2009).

Here is an example for a better understanding: according to the values of the insolation chart in figure 33, at 120-degree SW with the tilt angle of 30 degrees a PV output is 10% smaller than a perfectly south faced PV panel with the tilt angle around

35 degrees. Figure 34 illustrates the values of the insolation chart on each face of the building.

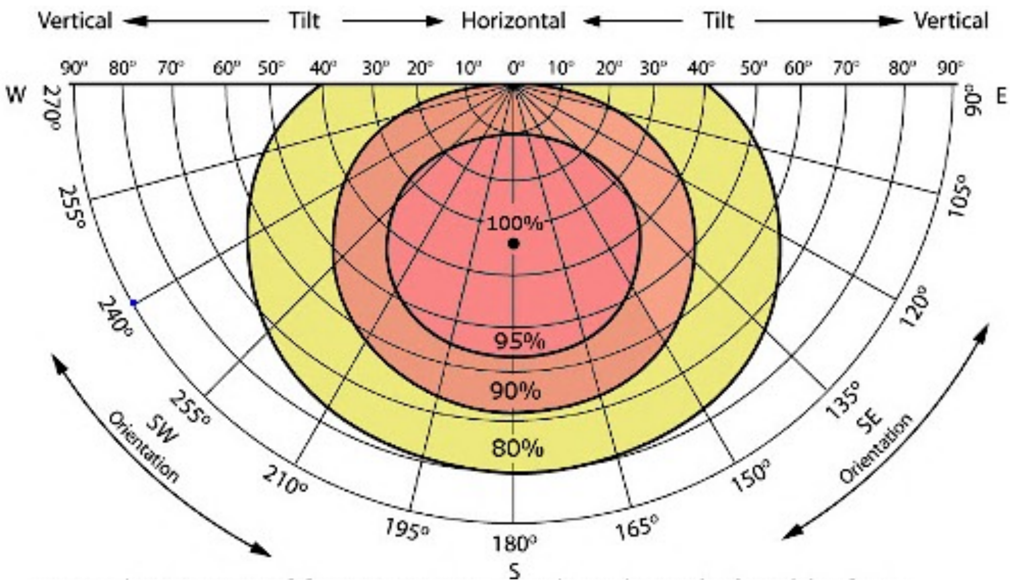


Fig.33 Comprehensive total insolation chart
Figure: based on Max Fordham & Partners (1999), Photovoltaics in Buildings: A design Guide. DTI URN: 99/1274

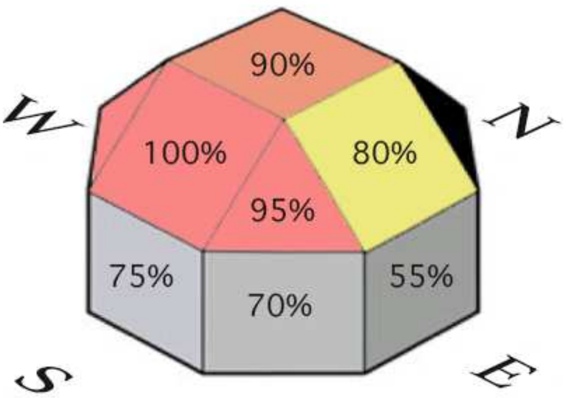


Fig.34 Insolation value of different faces based on various tilts and orientations (own graph)

7.2. Building envelope

PV modules can be installed into the building in various ways. The building envelope is the interface between the indoor ambient and the outdoor environment. BIPV elements produce electricity and same time function as building's components such as traditional walls, windows or roofing cladding.

Façade mounted solar cells replace the traditional view of the building to the spandrel glass and if they are installed in a large area of the façade they provide a remarkable source of power. However, to avoid unnecessary space heating and cooling caused by uncontrolled ventilation and to improve the efficiency of the ventilation system a specific level of airtightness needs to be achieved.

PV panels could be considered as shading elements that besides increasing the access to the sunlight would make additional benefit to the energy performance of the building by providing passive shading.

Roof-mounted PV could be the replacement for roofing cladding. Skylight PV system not only provides optimal use of solar energy but also creates an exciting architectural element. A high-performance BIPV system requires appropriate design based on the building loads, features of the building envelope and the type of PV system (Roberts & Guariento, 2009).

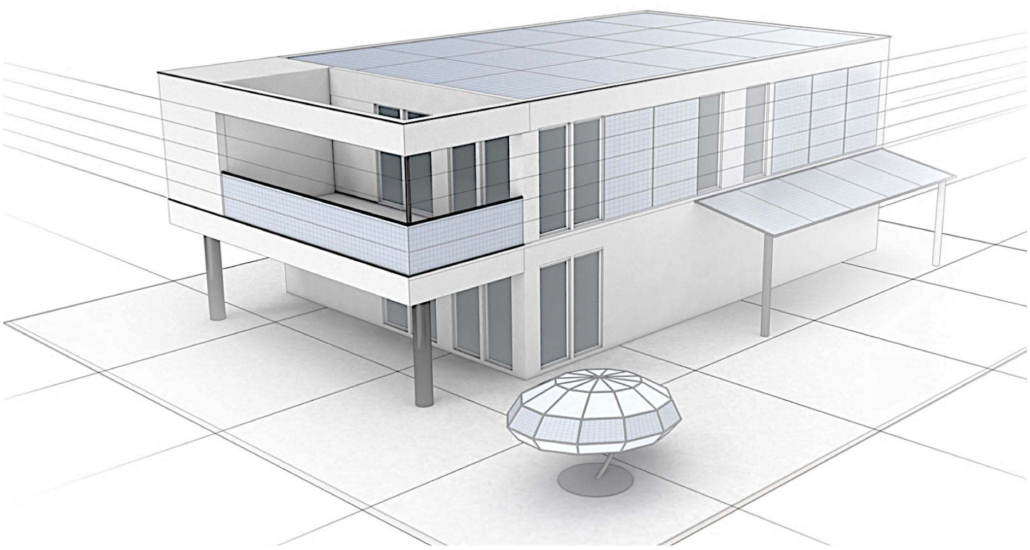


Fig.35 PV elements on building's envelope. Image courtesy of ertexsolar

7.3. BIPV mounting systems

PV panels can be mounted into the building envelope in various ways. In this chapter, different facade PV installation are described.

Shading systems (sunshades and sunscreens):

PV modules could be combined into shading features of buildings. Shading systems not only provide solar energy but also reduce the cooling loads of the building. External shading elements (louvers) can be both horizontal and vertical and can be installed either close or at a distance from the windows. Based on their size, weight and offset they are mounted into the façade by simply fixing them to the cladding frame or the building structure (figure 36). They can be movable and retractable (Roberts & Guariento, 2009).

The main issue regarding the external shading elements is durability since they sometimes don't resist the intense wind loadings. Also, cleaning and maintenance of the panels are difficult regarding the access limits. (Roberts & Guariento, 2009)

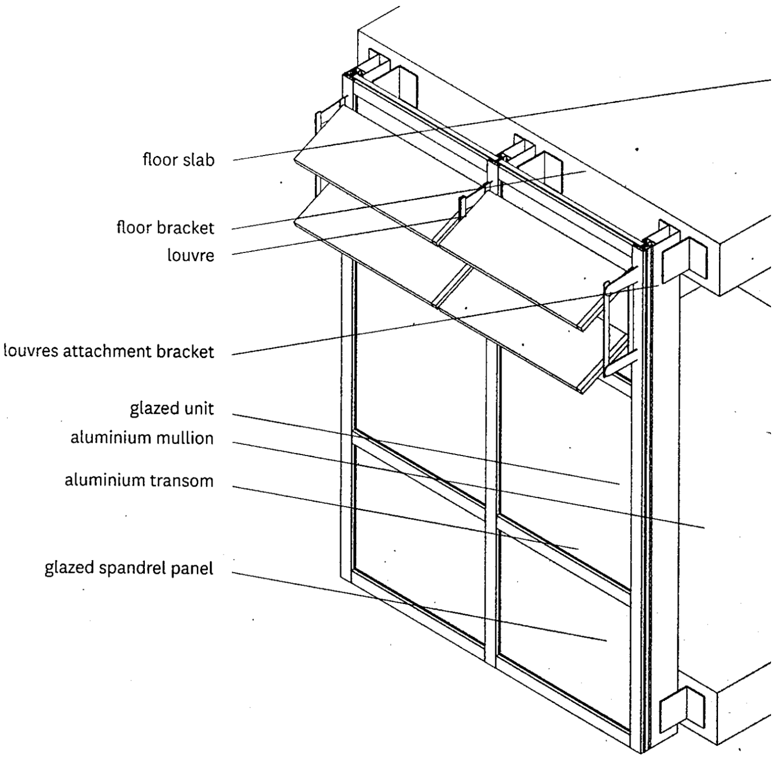


Fig.36 Features of a louvers (sun shading PV)
Source: Roberts & Guariento, 2009

Rainscreen systems:

Rainscreen claddings system consists of two parts: the external screen and the inner air space cavity that separates the rain barrier and the wind barrier. While the outer surface provides a great barrier to rain penetration, the inner part is kept dry and works as the air barrier (figure 37).

Installation of the rain screen panels into the building surface is done by aluminum fixing rails. The backing wall is made a typical material like brick, concrete or metal stud. The insulation layer must be applied to the external side of the wall. On the warm side of the insulation, a vapor barrier material must be considered to resist diffusion of moisture through the wall. And on the cold side of the insulation, a waterproofing membrane material could be applied (occasionally).

Rain screen systems are categorized into two types: the “drained and back ventilated” rainscreen and the “pressure equalized” rainscreen system. These two systems are distinguished by the different amount of water that is permitted to pass into the cavity (Roberts & Guariento, 2009).

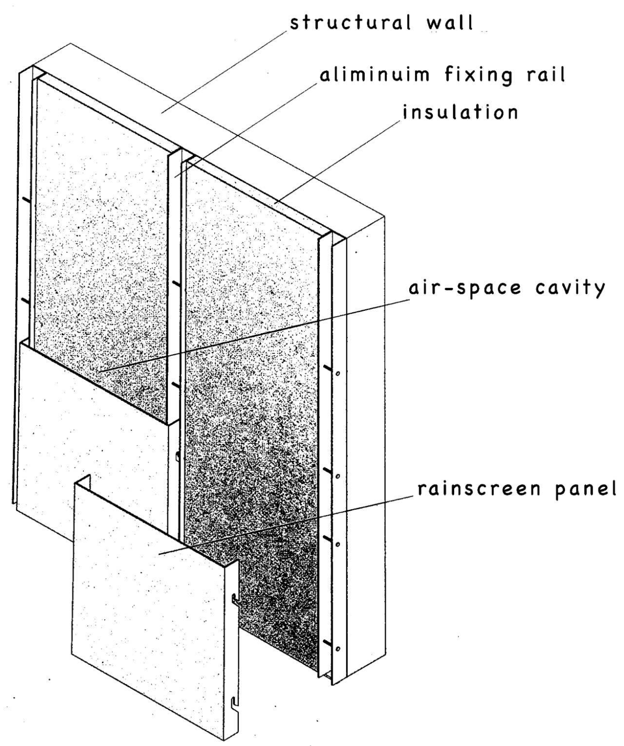


Fig.37 Schematic of rain-screen cladding system
Source: Roberts & Guariento, 2009

Stick-system curtain walls:

Curtain walls are divided into two types: stick systems and unitized panels. The two systems are distinguished by the type of fabrication and installation. Stick systems are known as traditional curtain wall systems in which the system components (mullions and transoms) are mounted on site. But unitized curtain walls are large panels which are pre-assembled in the factory and then transferred to the site to be mounted into the building (Roberts & Guariento, 2009).

Stick system curtain walls are only recommended to use for small and medium-size systems in low-rise buildings since for the high-rise buildings, the mounting process and providing the required capacity of such a large system would be very difficult and economically not reasonable (Roberts & Guariento, 2009). Figure 38 shows a stick-system curtain wall installation.

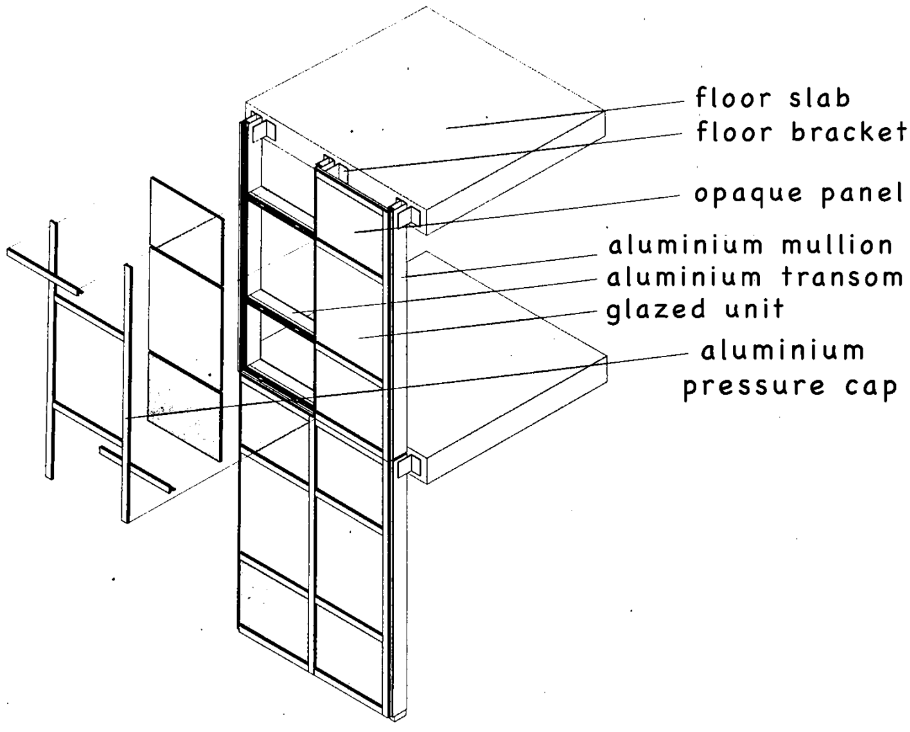


Fig.38 Schematic of stick-system curtain walls (Source: Roberts & Guariento, 2009)

Unitized curtain walls:

The unitized panel is a developed form of the curtain wall system and is developed to fix the problems regarding the installation of the traditional curtain wall system. This system consists of large pre-assembled panels that are as large as they can be delivered undamaged to the site of the building. The panel dimension is usually story-height and 1.5 - 9m width. All the required parameters of an external cladding of the building are provided in these panels such as insulation, vapor barrier element, fire protection, and internal finishing. For this reason, these panels are known as construction units or basic building blocks (Roberts & Guariento, 2009). Figure 39 is a schematic of the unitized curtain walls system.

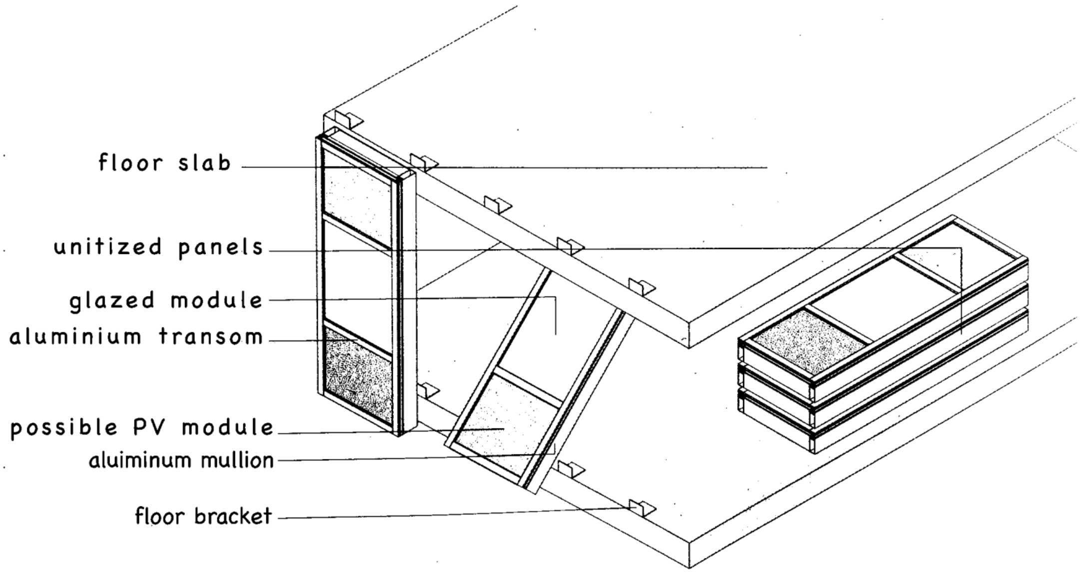


Fig.39 Unitized curtain walls system onsite storage and installation
Source: Roberts & Guariento, 2009

Double-skin facades:

The double-skin facade system provides the building with two separate skins that are divided by a buffer zone (a ventilated cavity). The inner skin is heat insulated and the cavity would be ventilated if required. The outer skin is where solar panels are mounted and make a glassy façade. Not only the outer skin generates solar energy but it also creates solar shading. Double-skin façade is a kind of system that is designed to be adjusted to the ambient conditions and improve the balance of the thermal comfort of the building. In this system, the optimum thermal comfort is provided by natural convection and without the intervention of the mechanical system. The captured heat inside the cavity can be used both passively and actively.

It's possible to install shading elements inside the cavity to protect the building from extreme solar irradiations. In winters the captured air inside the cavity will be heated by solar radiation. This process will improve the heat insulation of the façade and as well as the thermal performance of the building. Also, natural ventilation would reduce the need for mechanical air conditioning. And finally, the double-skin façade makes unique acoustic insulation at the open window position. The advantageous features of this system make it an appropriate selection for increasing the energy performance of a building (Roberts & Guariento, 2009).

Figure 40 on (side 1) shows the summer operation of a naturally ventilated façade. The air flows through the cavity space. During the day, the shutter is closed to reflect the radiations of the sun and the dampers are open to making a natural air circulation. On (side 2) the winter operation of a naturally ventilated façade is shown. Dampers are closed to trap the air in a closed area. During the day when the shutter is open, direct radiances are allowed inside the cavity to provide thermal energy and during the night the shutter is closed to reduce radiative losses of heat.

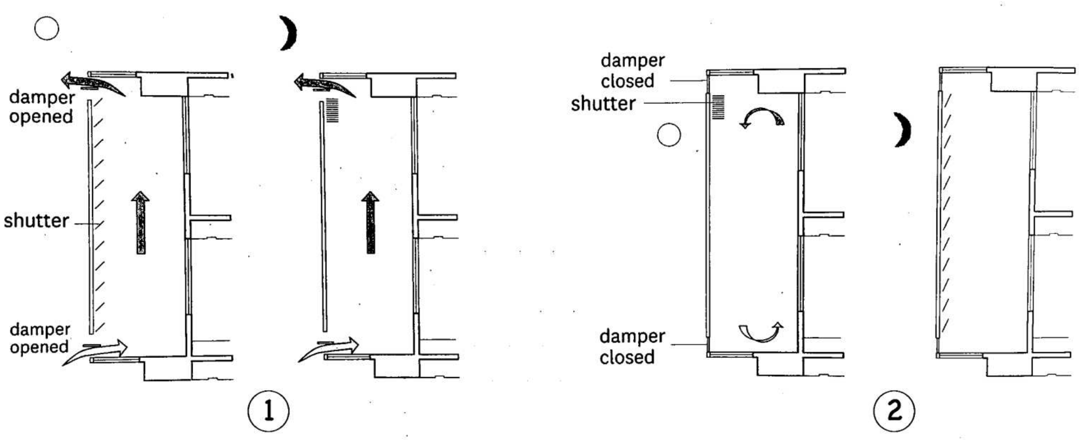


Fig.40 Summer operation (1) and winter operation (2) of a naturally ventilated facade
Source: Roberts & Guariento, 2009

Atria and canopies systems:

These systems are visually attractive since they provide sky sights and traces of sunlight within the building. But the risks of this system are undeniable such as too much heat gains in summer, too much heat losses in winter, difficult control of light transitions and roof leakage. Therefore, considering the control of indoor ambient conditions, the design of these systems is always challenging. Canopies systems are similar to atria, including a horizontal or slightly curved surface placed on top of the building. Figure 41 offers the details of horizontal overhead glazing system with PV modules.

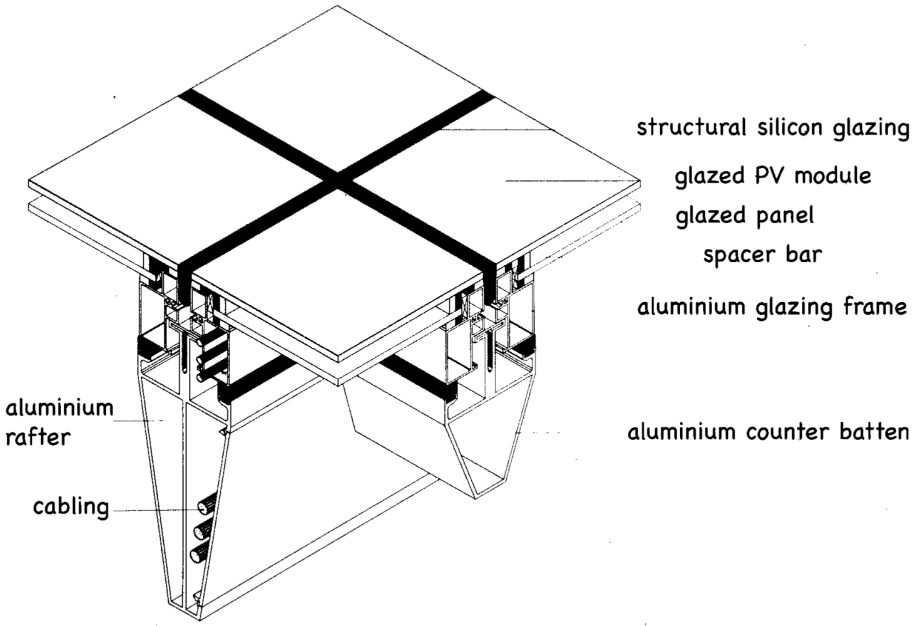


Fig.41 Details of horizontal overhead glazing system with PV modules
Source: Roberts & Guariento, 2009

Residential systems:

Residential PV systems are categorized as apartment blocks and low-rise houses. Although domestic PV systems and commercial building systems are similar in many ways, some parameters distinguish these systems such as energy demand of the buildings, production capacity of systems and installations.

The main challenge of PV installation in apartment blocks is related to small dimensions of the façade. Therefore, either curtain walls would have small portions of the area or the traditional walls are considered through the construction of the building. Also, residential buildings have stricter regulations regarding energy performance.

Recommended PV systems for apartment blocks are shading PV elements, rain screen systems, stick-systems, utilized systems (for high-rise apartment blocks) and roof-mounted PV systems. For low-rise traditional houses, proper PV options are rain screen systems (for vertical façade) and roof-mounted systems (Roberts & Guariento, 2009).

7.4. Cladding design (inclined PV panels with battery storage)

The inclined posture of the cladding would improve the performance of PV panels. The best position of inclined cladding south regarding the low height of the sun in winters. In the summertime that the sun is higher, the inclined units provide some shading to the windows beneath. Another benefit of cladding design is that every single unite is supported separately by an individual connection to the system, therefore, if when a damaged unite needs to be repaired or replaced the whole system will not be influenced during the restoration process.

Inclined PV panels with battery storage are the advanced forms of cladding design (as shown in figure 42). In this schematic β is the tilt angle of the PV panel which is the critical parameter regarding energy generation. "*The vertical dimension is lv, the horizontal overhang or "bottom" is lo, and the panel dimension in landscape format is lp. The section of the wedge on the interior part of the building is similar to a window casement approximately eight centimeters thick to accommodate the battery bank and wall plugs."* (A. Kim et al., 2019: 4)

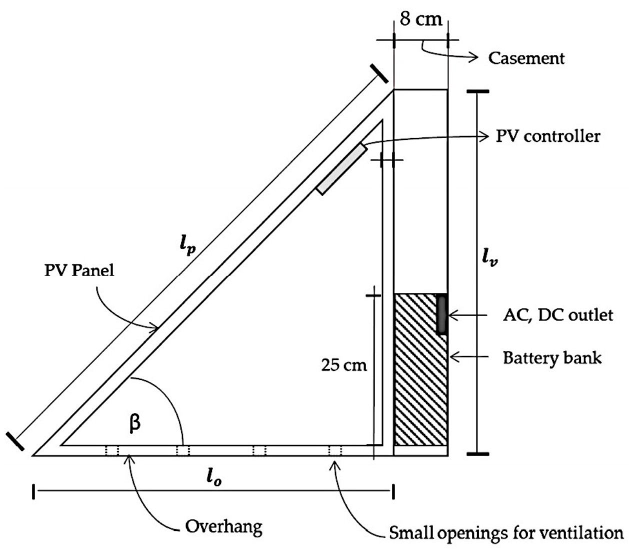


Fig.42 Tilted building-integrated PV (Source: Amy A. Kim, et. al, 2019)

7.4.1. Double wedge cladding

Inclined panels would create shadows over the lower unites. This is a drastic concern regarding system performance. To overcome this problem the design of "double wedge cladding" has been offered. As shown in figure 43, the lower part of the cladding is considered as a nonfunctional tilted wedge that doesn't create any shadow over the lower PV units.

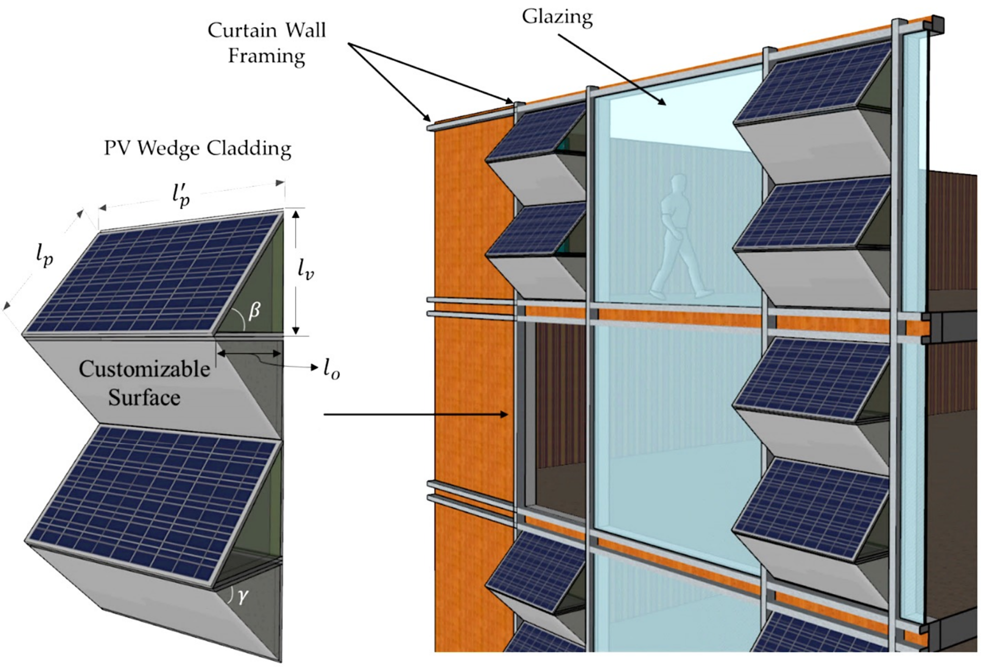


Fig.43 Double wedge formation of cladding to mitigate shadows: When β=γ= 45°, the height of the double wedge cladding is $2l_v$ (Source: Amy A. Kim, et.al, 2019)

7.5. Examples of innovative and awarded BIPV projects

BMW Welt Munich

A remarkable feature of BMW Welt in Munich it’s the large BIPV system, where 3,660 solar modules are mounted into the structure of the roof, within the area of 16500 m2. The minimum output of the system is 823 kWp, which is used for the heating and the air conditioning of the building.

Features of the system:

- Location: Munich, Germany
- System output: 823 kWp
- Type: unframed modules with black background foil
- Architect: Coop Himmelb (l) au, Vienna
- Client: BMW, Munich
- PV modules: solar watt

Fig.44 BMW Welt Munich PV power plant (Source: BMW GROUP)

Energy plus child day-care center in Marburg

The exterior façade and roof of the KITA Marburg daycare center are black homogeneous PV modules. The specific design of the modules was achieved through a certified ink technology which provides covers the reflective soldered tapes. The installed capacity of 52 kW generates nearly 50.000 kWh per year which covers 50% of the energy demand of the center (Federal Association of Photovoltaic Austria).

Features of the project:

- Architects: opus Architects BDA
- Location: Marburg, Germany
- Project year: 2014
- Client: Magistrate of the City of Marburg
- System output: 50000 KWh/year
- PV modules: ertex solar

Fig.45 Energy-plus child day-care center in Marburg, Germany. West view
Image Courtesy © Eibe Sönnecken

Fig.46 Energy-plus child day-care center in Marburg, Germany. Southeast View
Image Courtesy © Eibe Sönnecken

New +E residential building in Zurich

The attractive exterior surfaces of the residential house offer shades of dark red, violet and silver due to the invisible attached glass panels with photovoltaic elements. The electricity produced by the building's envelope is double the building's loads (Federal Association of Photovoltaic Austria, 2018).

Features of the project:

- Architects: huggenbergerfries
- Location: Zurich, Switzerland
- System output: 56000 kWh/year
- Type: Completely activated building envelope
- PV modules: ertex solar
- Award: Austrian innovation award for building-integrated photovoltaics. (Winer 2018)

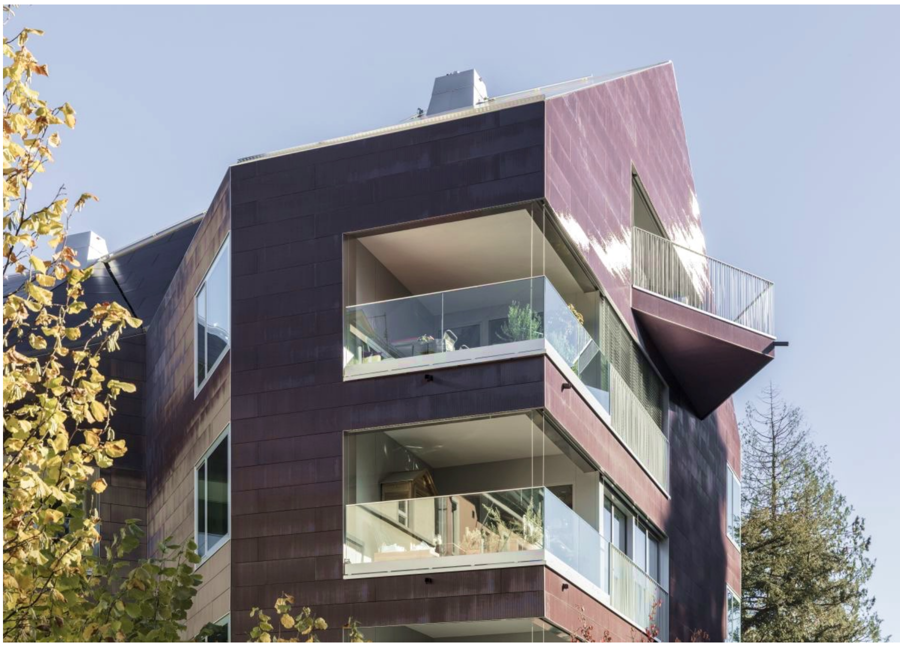


Fig.47 The most innovative Residential BIPV project. Zurich, Switzerland
Image Courtesy © Beat Buhler

Energy plus office tower in Vienna

The office tower of TU Wien is the largest BIPV project in Austria. The total module area of the system is 2199 m2. Modules are mounted in 11 stories in three different sizes. Modules are installed into the façade, on the roof, in the staircase and as shading elements for shadowing the terrace. The total annual yield of the system is 248.804 kWh that is used by the building and the excess production of the system is distributed to the neighborhood buildings and the Getreidemarkt area (Federal Association of Photovoltaic Austria, 2018).

Features of the project:

- Architects: Schöberl & Pöll GmbH
- Location: Vienna, Austria
- System output: Roof: 97.8 kWp | Facade: 230.6 kWp
- Type: Façade: frameless modules (glass-glass modules), Staircase: high-energy triple glazing (VSG pane), Roof: glass-film modules
- Client: TU Wien
- PV modules: PVP
- Award: Austrian innovation award for building-integrated photovoltaics. (Winer 2018)

Fig.48 Energy plus office tower (TU Wien) in Vienna
Image courtesy © Schöberl & Pöll GmbH

NEW Blauhaus university Niederrhein

"The project is a cooperation between the Niederrhein University of Applied Sciences and the Energy and water supplier NEW and serves to present innovative Developments in the energy sector." (Federal Association of Photovoltaic Austria, BIPV Innovations awards 2018: 23)

PV elements are mounted into the façade within the inclined shimmering blue glass units. This building is known as a zero-emission building by considering the passive house standards.

Features of the project:

- Architects: Schöberl & Pöll GmbH
- Location: Mönchengladbach, Germany
- System output: 81,500 kWh/year
- Type: facade
- PV modules: ertex solar
- Award: Austrian innovation award for building-integrated photovoltaics (Winer 2018)

Fig.49 NEW Blauhaus university Niederrhein.
Image courtesy © Andreas Horsky

8. Challenges of BIPV system

BIPV as an energy provider system is dealing with some challenges which are categorized in different groups as follows. The first group of challenges is location restrictions regarding PV placement. The second group is technical challenges related to PV mounting, material, PV performance, and stability of the utility grid system. Next are the BIPV market limitations and price.

8.1. Location restrictions

Location restriction regarding PV placement are:

- **Tilt and orientation of the building** (as discussed in chapter 7.1.1.)
- **Useful output and daily insulation** (as discussed in chapter 4.2.1.)
- **Overshadowing and partial shadowing risk:** One of the main factors that impact on PV performance is overshadowing. Even a small shaded part of the system would affect the output of the system. Shadows produced by neighboring buildings, tall constructions, trees, vegetation, birds and even shadow of cabling lines over the building can affect the system. And if these elements are not already existed on the location, the probability of their existence in the future that could anyhow affect the system must be considered. Also, self-shading by the own building's components must be avoided.

Overshadowing minimizing strategies:

Concerning overshadowing: PV elements should be installed at the northern surface of the building which is considered permanently unshaded. Another strategy is installing the system in multiple orientations (north, east/west). In the case of roof installations, PV elements must be distanced from neighboring buildings' boundaries. The system should be designed in multiple string arrangements considering micro inverters and bypass diodes.

Concerning self-shadowing: For the facade installations, the staircase should be considered on the north side of the building. For roof installations, the shading elements should be located on the northern part such as chimneys, ventilation stacks, water tanks, and lift rooms. Trees should be located in the appropriate distance from the PV façade.

8.2. Technical challenges/considerations

Following parameters make a summary of technical challenges and considerations of BIPV systems;

Structural supports:

Building's cladding systems are exposed to all types of weather conditions including rain, snow, wind loads and storms and they are expected to withstand harsh conditions. Also, they are considered loading barriers against the imposed forces, impact loads and loading related to the cleaning and maintenance. Other parameters regarding the structural design of the cladding system are frame movements and tolerances, air-tightness, weather-tightness, thermal and acoustic performance, fire safety and glass thermal stress (Roberts & Guariento, 2009).

Material:

Generally, BIPV units generate less electricity than typical flat PV panels because they contain less semiconducting materials. This issue would expand the dimension of a PV installation, especially on vertical facades.

PV integration in refurbishment:

Working through limitations of the existing structure and the same time following the local regulations is the biggest challenge of PV integration in refurbishment. The best opportunity for PV integration appears when the performance improvement of the façade or roof is the main goal of refurbishment.

Effect of air mass on PV performance:

Air mass is the combination of different factors such as temperature, dust, pollution and relative humidity. Each of these factors would affect the performance of the PV system. Dust accumulation would decrease the reaching of irradiations and results in the reduction of PV system output. Temperature gains would also decrease the system output (as discussed before). Increasing relative humidity would also affect PV performance slightly. The frequent maintenance program is required to minimize this problem as much as possible.

Stability of the grid:

Grid's stability is concerning when the power consumption is less than the power generation and a reverse flow happens in the distribution line. This could lead to some issues in distribution grid. since the distribution grid is not prepared for the reverse flow. The issues can appear as:

- Voltage problems such as voltage rise and possible excess of the upper voltage limit. To mitigate this issue, while connecting the consumers and generators, distribution system operators must make sure that the voltage will not exceed the limits under the worst-case scenario. (EPIA Report 2012)

- Equipment overload regarding the lines of transformers (EPIA Report 2012).
  "*the conventional approach would be to connect the new generator to a stronger part of the grid, to limit temporarily the power that can be connected, or to reinforce the network. The first option is not always applicable, the second option contradicts policy objectives on the deployment of renewables, and the third requires sometimes costly investments.*" (EPIA Report 2012: 59)

Following figure shows the PV integration on distribution system from low voltage to medium and high voltage.

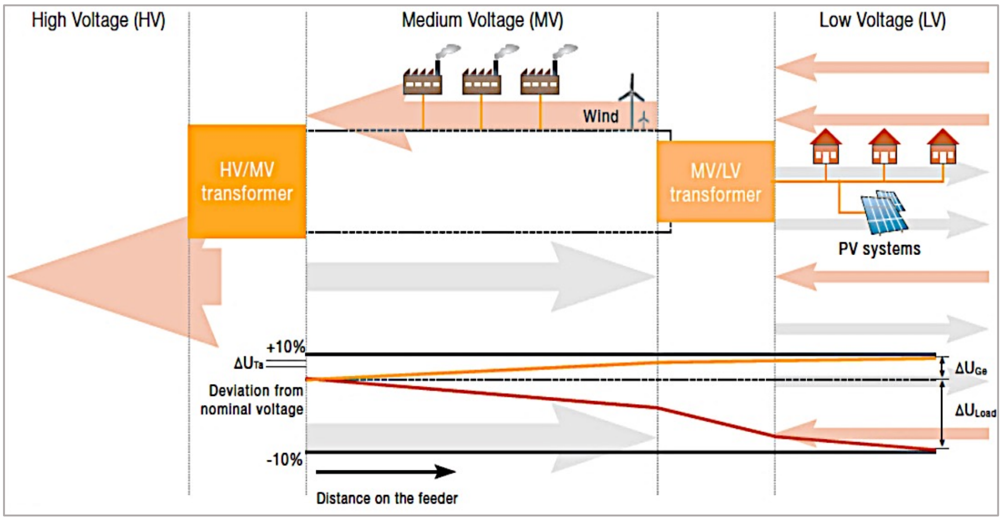


Fig.50 PV integration on distribution system (from low voltage to medium and high voltage)
Source: EPIA Report 2012

8.3. BIPV market limitation and price

Market Limitations:

Facade PV systems are custom-design elements and are manufactured in various types, also applications of BIPV are limited to the residential and commercial buildings. So, compare to ground-mounted PV panels BIPV has a smaller potential of manufacturing pattern expansion. Although the BIPV market share has been growing, due to the design limitations and the high price of the BIPV manufacturing process, it's not known as a cost-reducing system in the market.

The main growth of the PV market belongs to the US and Europe, which together account for 70% of the global market share, hence the PV investment is predicted to grow further in these regions in the following years. Other countries like Japan and China also represent attractive markets but with a lower rate of investments (PVSITES, 2016). Figure 51 shows the current and forecasted BIPV market in different regions.

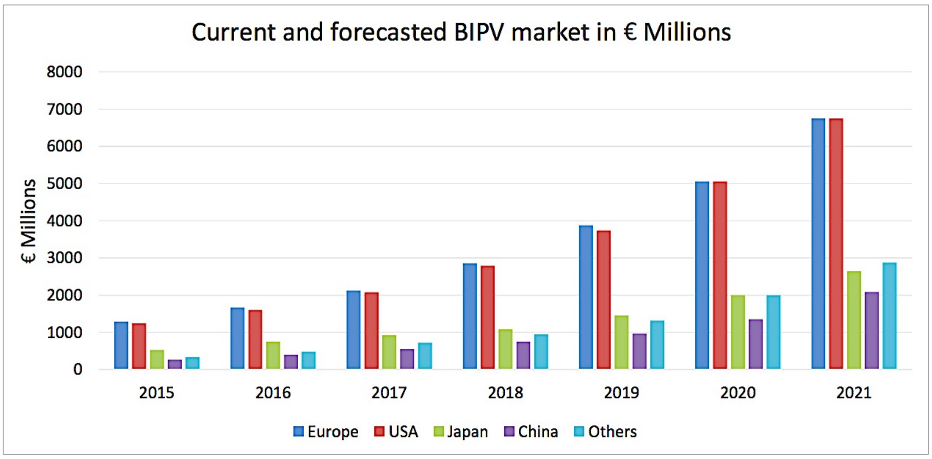


Fig.51 Current and forecasted BIPV market by regions in € million
Source: PVSITES, 2016

BIPV Price:

Following parameters explain why BIPV panels have higher price than flat PV elements:

- *"Customer perception that these products should cost more because of their specialty function and their willingness to pay premiums for that function.*
- *Supply chain issues for products and services (e.g., difficulties in establishing distribution channels and hence getting product to market).*
- *BIPV modules may include additional materials (e.g., adhesives and framing and flashing materials).*
- *Additional labor costs deriving from specialized architectural design, engineering design, and installation, according to a Greentech Media report.*
- *It is important to note that BIPV prices are variable by market and by application (i.e., structure-specific design of the module), and so pricing is something of a moving target."* (Lowder, 2012, The Challenges of Building-Integrated Photovoltaics).

Despite the higher price of BIPV systems, they can reduce some costs of the building construction considering the possibility of their replacement to the traditional building materials. The lifespan of a facade PV system is over 30 years and the payback period of the system is 10 to 15 years. Serving 2-3 times longer than their payback period makes these systems economically attractive and reasonable.

Roof PV elements are more standardized and are offered in several materials. Due to the large demands of rooftop PV units in the market, they generally have less price than façade PV elements.

Financial Supports for BIPV:

Financial supports are great motivations for developing green energy sources, decentralizing energy supply and saving the environment. The authority of most countries considers financial supporting schemes for BIPV developers. The supporting schemes are defined in several criteria and are available for investors, consumers, and stakeholders. The owner of the BIPV business models would also benefit from the supporting schemes. In EU regions, special supporting options are considered for the self-consumption BIPV business to develop the advantages of grid-parity (European regulatory framework for BIPV, 2016).

Here are the public supporting mechanisms and the energy policy requirement to promote BIPV technology:

Feed-in tariff: FIT used to be the main traditional supporting method that is being removed from the supporting schemes due to the development of grid-parity. And instead, new regulations and frameworks are being established for supporting the self-consumption PV models.

Income tax credits: This option excludes a part or the whole expenses of the PV installation from the taxable earnings. This method supports the economic viability of the investors and producers by minimizing their financial pressures regarding the PV business models.

Capital subsidies: Subsidies are available for the system equipment and (or) the whole mounted PV system to moderate the high costs.

Renewable portfolio standards (RPS): This option obliges the power supply companies to provide electricity from renewable sources. This obligation is issued to promote shifting to renewable energy sources on a global scale.

Sustainable building requirements: These requirements should be provided when the PV system is considered as a method for reducing the energy footprint of the building or as a mandatory option of the building’s development (European regulatory framework for BIPV, 2016).

9. Simulation of BIPV system of an office building

In this chapter, a seven-storey office building is simulated with the same features in three different cities in the world (Vienna, Tehran and Melbourne) to assess the energy performance of the given building in each location. As shown in figures 53 to 55, the indoor area of the building consists of 20 office units, entrance area, staircase, lift box and shared corridors. The attic (loft area) provides the electrical room.

Fig.52 Indoor plans of the simulated office building (own design)

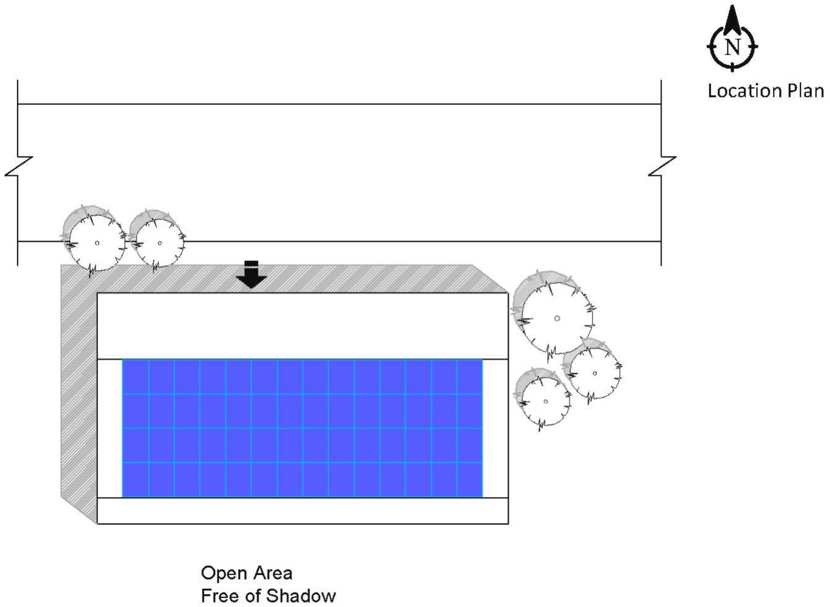


Fig.53 Location plans of the simulated office building (own design)

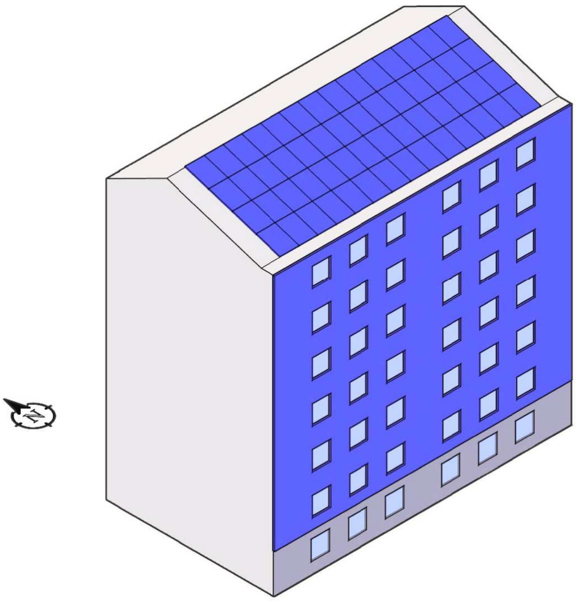


Fig.54 3D model of the simulated office building (own design)

The detailed features of simulation cases are as follows:

1. Region: (1) Vienna, Austria. (2) Tehran, Iran. (3) Melbourne, Australia.

Latitude and longitude: data in table 7

Average global horizontal irradiance: data in table

Table.7 Latitude and longitude of the given locations.
(Data from PV*SOL online software)

Location	Lat.	Lon.
Vienna	48.2083° N	16.3725° E
Tehran	35.7006° N	51.4013° E
Melbourne	37.8142° S	144.9631 °E

Table.8 Average global horizontal irradiance of the given locations.
(Data from PV*SOL online software)

Location	Average GHI
Vienna	1199.9 kWh/m²
Tehran	1828.4 kWh/m²
Melbourne	1533.4 kWh/m²

2. Building type: office building

Height and storeys: 7 stories including the ground floor. The floor-to-floor height is 3.20 m for every storey.

Useful indoor area: ground floor 250.90 m2, typical floors 266.47 m2

3. Energy systems: BIPV + Hybrid HVAC

Electricity: Grid- connected BIPV system

Type of the BIPV: Façade mounted PV in the area of 420 m2 + Roof mounted PV in the area of 180 m2

Technology of PV modules: 300W monocrystalline high-efficiency

Cell conversion efficiency: 25%

Module conversion efficiency: 16%

Individual model dimension: for the façade modules: customized at floor height and 150 cm width. For the roof modules: 150cm x 200cm

HVAC: hybrid system (PV + TABS + heat pump)

Description of the BIPV system: The system consists of façade-mounted PV modules (vertical position) and inclined roof-mounted PV modules with optimum tilt for each location. The output of the system is directly used by the building for the lighting, electric equipment, heating and cooling.

Description of the HVAC system: The energy demand of the building for heating, ventilation, and air-conditioning is provided from a hybrid system by combining three systems of PV, TABS and heat pump. As the PV modules generate solar electricity and supply the building, the TABS system provides radiant heating and cooling from the concrete slabs in floors, ceilings, and walls and minimizes the energy demand for heating and cooling. Heat pump is the third part of the HVAC system to pump the heat from the thermal source to the needed point. The heat-pump works by the electricity generated from the PV modules.

The following two figures illustrate the details of the façade-mounted PV and roof-mounted PV unites of the simulated BIPV system.

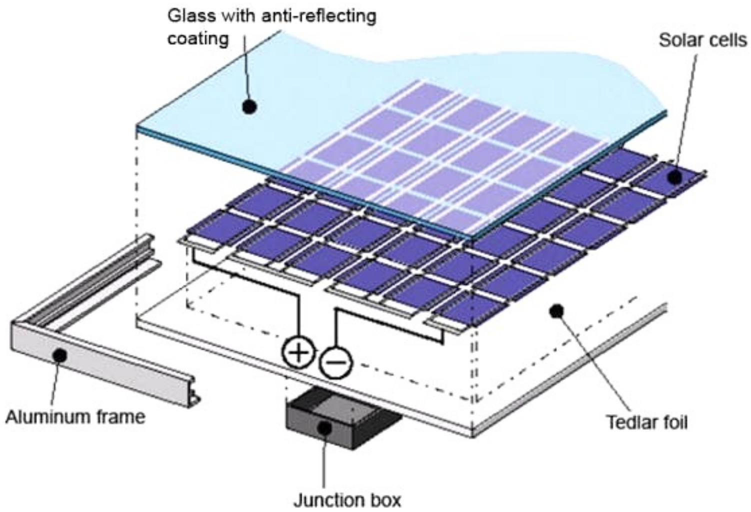


Fig.55 Façades glass curtain wall with PV Modules Cladding
Source: FASECbuildings

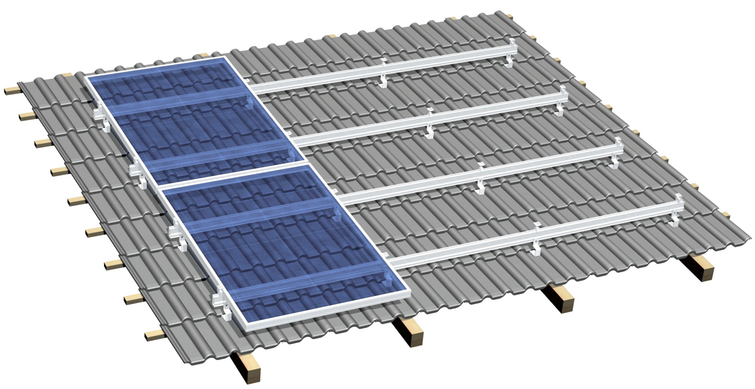


Fig.56 Roof-mounted PV modules
Source: S:FLEX, Product Catalogue 2013

9.1. Case studies (1,2,3)

In this chapter, the simulated BIPV system of the given office building will be assessed in three different locations. The annual output of the system will be calculated based on the given data from the previous chapter. These calculations would show how the system performs in three different locations.

According to the Department of Energy (DOE), the average number of kilowatt-hours per square foot for a commercial building is approximately 22.5 (74 kWh/m2) per year. It means the annual electricity consumption of the simulated office building with a useful area of 1850 m2 would be around **137,000kwh/y**. But the total energy consumption of the building would be 13% reduced by the TABS system. Therefore, the estimation of energy consumption of the simulation building is a value of around **120,000kWh/y.**

The global formula to estimate the electricity generated in output of a photovoltaic system is:

$$E = A * r * H * PR$$

E = Energy (kWh)
A = Total solar panel Area (m2)
r = solar panel yield or efficiency (%)
H = Annual average solar radiation on tilted panels (shadings not included)
PR = Performance ratio, coefficient for losses (range between 0.5 and 0.9, default value = 0.75)

Then the estimation of the BIPV system output for each case study would be as follows:

Case 1. Vienna, Austria

- Average global horizontal irradiance is 3.4 kWh/m2.day for the horizontal surface.
- Vertical surface facing south has 75% efficiency compared to the optimum tilt
- The south face is free of shading
- Balance of the system losses is around 15%.

Based on the features of the PV system, estimation of the total output would be as shown in following table:

Table.9 System output of the case study 1 (Vienna)

Location: Vienna, Austria	
Load profile: Commercial building G1*	Latitude: 48.2083537 °
Annual global irradiation: 1199.9 kWh/m²	Longitude: 16.3725042 °
PV type: 300W monocrystalline	Average temperature: 12.2 °
Building consumption: 120000 kWh/y	
Systems Output	
Roof-mounted with the optimum tilt 35°	**Vertical façade mounted**
Annual PV energy: 21440 kWh	Annual PV energy: 34369 kWh
Spec. annual yield: 1191.08 kWh/kWp	Spec. annual yield: 818.32 kWh/kWp
Performance ratio: 89.26 %	Performance ratio: 91.58 %
Own consumption: 18763 kWh	Own consumption: 28280 kWh
Thereof grid feed-in: 2993 kWh	Thereof grid feed-in: 6482 kWh
Own consumption by PV:	Own consumption by PV:
Total output: 55809 kWh/y	
Avoided CO2 emissions: 29857 kg/year	
Total consumption by the building: 47043 kWh/y	

Data and calculations: PV*SOL online software.
G1: BEDW load profile business G1 (commercial buildings)

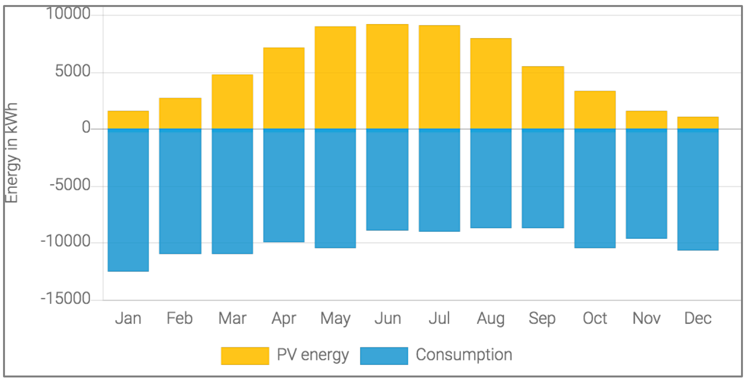


Fig. 57 Production of the PV system and consumption of the building in each month (case 1) (own chart)

Case 2. Tehran, Iran

- Average global horizontal irradiance is 5 kWh/m2.day for the horizontal surface.
- Vertical surface facing south has 75% efficiency compared to the optimum tilt
- The south face is free of shading
- Balance of the system losses is around 15%

Table.10 System output of the case study 2 (Tehran)

Location: Tehran, Iran	
Load profile: Commercial building G1	Latitude: 35.7006177 °
Annual global irradiation: 1828.4 kWh/m²	Longitude: 51.4013785 °
PV type: 300W monocrystalline	Average temperature: 18.4 °
Building consumption: 120000 kWh/y	
Systems Output	
Roof-mounted with the optimum tilt 35°	**Vertical façade mounted**
Annual PV energy: 30897 kWh	Annual PV energy: 44951 kWh
Spec. annual yield: 1716.52 kWh/kWp	Spec. annual yield: 1070.27 kWh/kWp
Performance ratio: 86.24 %	Performance ratio: 90.44 %
Own consumption: 25961 kWh	Own consumption: 36213 kWh
Thereof grid feed-in: 4936 kWh	Thereof grid feed-in: 8738 kWh
Own consumption by PV:	Own consumption by PV:
Total output: 75848 kWh/y	
Avoided CO2 emissions: 40580 kg/year	
Total consumption by the building: 62174 kWh/y	

Data and calculations: PV*SOL online software.

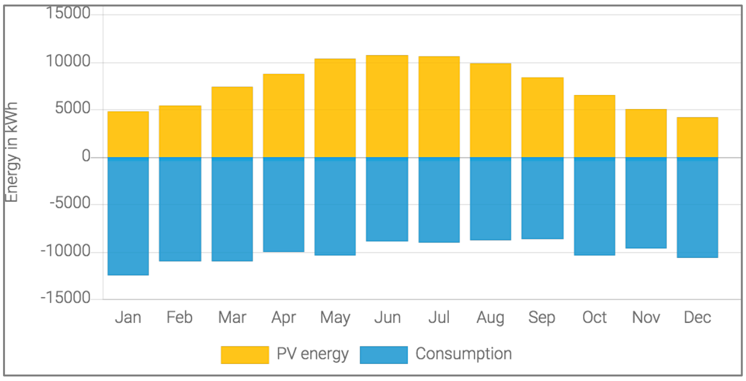


Fig.58 Production of the PV system and consumption of the building in each month (case 2) (own chart)

Case 3. Melbourne, Australia

- Average global horizontal irradiance is 4.2 kWh/m2.day for the horizontal
- Vertical surface facing south has 75% efficiency compared to the optimum tilt
- The south face is free of shading
- Balance of the system losses is around 15%

Based on the features of the PV system, estimation of the total output would be as shown in following table:

Table.11 System output of the case study 3 (Melbourne)

Location: Melbourne, Australia	
Load profile: Commercial building G1	Latitude: -37.8142176 °
Annual global irradiation: 1533.4 kWh/m²	Longitude: 144.9631608 °
PV type: 300W monocrystalline	Average temperature: 14.5 °
Building consumption: 120000 kWh/y	
Systems Output	
Roof-mounted with the optimum tilt 38°	**Vertical façade mounted**
Annual PV energy: 26627 kWh	Annual PV energy: 40327 kWh
Spec. annual yield: 1479.28 kWh/kWp	Spec. annual yield: 960.16 kWh/kWp
Performance ratio: 88.48 %	Performance ratio: 91.24 %
Own consumption: 22377 kWh	Own consumption: 32250 kWh
Thereof grid feed-in: 4250 kWh	Thereof grid feed-in: 8077 kWh
Own consumption by PV: 84%	Own consumption by PV: 80 %
Total output: 66954 kWh/y	
Avoided CO2 emissions: 48000 kg/year	
Total consumption by the building: 54627 kWh/y	

Data and calculations: PV*SOL online software.

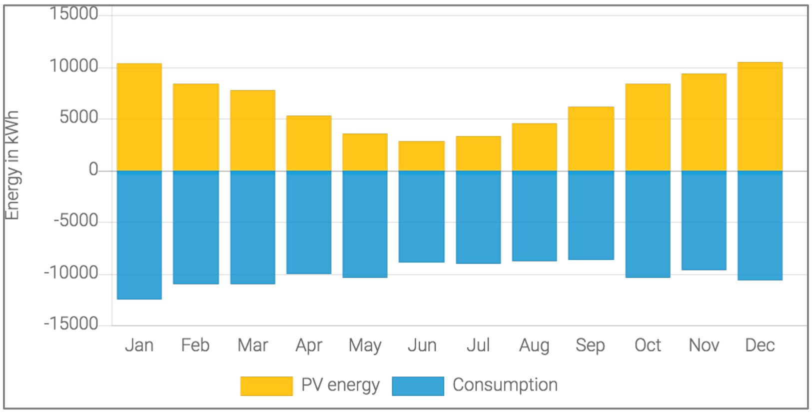


Fig.59 Production of the PV system and consumption of the building in each month (case 3) (own chart)

Comparison of the results:

the calculations of the output of the systems show that between the three given locations the system has the highest performance with a total output of 75848 kWh/y in Tehran as a result of the high global irradiance, whereas Melbourne has the second place with an annual output of 66954 kWh. Vienna comes to third place with 11000 kWh fewer annual output compared to Melbourne.

If the whole PV output is consumed by the building it would cover 63% of the boiling's loads in Tehran, 56% of the building's load in Melbourne and 46.5% of the building's load in Vienna. According to the calculation results, the simulated BIPV system would reduce between 30 – 48ton CO_2 emissions per year in each location.

9.2. Photovoltaic calculation softwares

"Professional photovoltaic software(s) and calculators to download:

- ***PV F-CHART (USA):*** *PV F-CHART is a comprehensive photovoltaic system analysis and design program. The program provides monthly-average performance estimates for each hour of the day. The calculations are based upon methods developed at the University of Wisconsin which use solar radiation utilizability to account for statistical variation of radiation and the load.*

- ***PVComplete:*** *Pvcomplete is a software that use Autocad and System Advisor Model Models energy production for your PV design. Shadow modelling: Draw obstructions and our software will draw in shaded areas for you based on latitude, azimuth and object height.*

Online Professional photovoltaic softwares and calculators:

- ***SOLARGIS – PVPLANNER:*** *Simulation tool for planning and optimisation of photovoltaic systems using climate and geographic data at high temporal and spatial resolution and newgeneration high performance algorithms.*

- ***Archelios PRO - solar Trace Software:*** *This PV software permits to evaluate solar radiation of a site, to design a photovoltaic system and calculate the energy produced and the profitability. Archelios is for projects up to 50kWp, Archelios Pro is for projects of any size.*

Online free photovoltaic software:

- ***PV*SOL online (GE):*** *PV*SOL online is a free tool for the quick and easy calculation of grid-connected photovoltaic systems (roof integrated/parallel or roof/ground mounted). After inputting basic data for the location, load profile, annual energy consumption, module and inverter, the automatic configuration manager searches for the optimal module and inverter connections."* (https://photovoltaic-software.com/)

10. Conclusions

This work is aimed to offer practical knowledge towards creating a better future by preserving the natural environment. Using clean energy is in collaboration with the reduction of climate changes and shifting seasons. On the other hand, CO2 emission is a big concern for the world and its reduction is essential and has turned into an obligation. CO2 reduction is only possible through the transition to sustainable living and using renewable energy sources.

Regarding the necessity of sustainable green transition, the European Commission has developed the European Green Deal as a roadmap with actions to enables the European citizens and businesses to move clean circular economy, restore biodiversity and cut the pollutions. The target is that Europe turns into the world's first climate-neutral continent by 2050 (European Commission). Achieving this goal requires the comprehensive collaborations of the public sector, businesses, and stakeholders.

Technical assessments and analysis of PV systems in this work are combined with the features of sustainable building designs to investigate the PV integration into the built environment. The estimations of the PV performance in three case studies are acceptable in this work.

BIPV technology has a bright future, considering that it's becoming more available, quick, easy and cost-effective. Improving the guaranties of the PV system makes it more interesting. Also, supporting schemes and subsidies from the authorities increase the motivations for PV investments. In conclusion, the PV business creates a wining pattern for every side involved, the natural environment, the governments, building owners and utility services.

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List of Abbreviations:

a-Si	Amorphous silicon
AC	Alternating current
BIPV	Building integrated photovoltaic
BOS	Balance of the system
CAD	Computer-aided design
CAGR	Compound Annual Growth Rate
CdTe	Cadmium telluride
CIGS	Copper indium gallium selenide
CIS	Copper indium selenium
CO2	Carbone dioxide
DC	Direct current
DHW	Domestic hot water
DOE	Department of energy
EVA	Ethylene vinyl acetate
GaAs	Gallium arsenide
GaInP	Gallium indium phosphide
Ge	Germanium
HJT PV	Heterojunction technology photovoltaic
HVAC	Heating ventilation air-conditioning
IEA	International Energy Agency
InGaAs	Indium gallium arsenide
IEQ	Indoor air quality
kWh	Kilowatt hour
kWp	Kilowatt peak
MPPT	Maximum power point tracker
NOCT	Nominal operating temperature
NZEB	Net zero energy building
PMV	Predict the mean value
PPD	Predicted Percentage Dissatisfied
PV	Photovoltaic
RPS	Renewable portfolio standards
TABS	Thermally activated building mass
TPU	Thermoplastic polyurethane
WBGT	Wet bulb globe temperature
Wp	Watt peak

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