BIPV Form Factor as an Approach for the Energy Performance of Buildings Exemplified for the Location of Tabriz (Iran)

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ABSTRACT

Building form and envelope surfaces play a significant role in energy performance assessment and the generated energy potential of the building integrated photovoltaics (BIPV) concept in early-stage design. To increase the energy efficiency level, form factor (FF) is proposed as a helpful tool that provides a strong relationship between the exposed surface areas and the treated floor area (TFA).

This research aimed at developing a parametric study to determine the related balance (correlation) between the TFA and needed BIPV area in the form enclosure to meet specific primary energy demand (SPED) according to the passive house standard (PHS). For this purpose, various form types including square, rectangle, L, and T shapes-which is derived of four modular cubes- classified based on the same form factor (FF). Optimal form selection per group carried out through the BIPV potential evaluation for the exposed surfaces in six azimuths separately. Afterward, BIPV efficiency level examined by its utilization factor and coverage index scenarios based on façade and roof combination priorities.

The results indicate that the generated energy sufficiency is affected by the form configuration and its orientation. Additionally, the optimal BIPV-based FF value of 0.71 implies the priority of roof-based scenarios for less BIPV utilization. Finally, the correlation value for the BIPV coverage index relative to the total envelope for the optimal forms and orientation is higher than 0.92, which can be extended to other forms in different locations as an assessment model.

Keywords: Building integrated photovoltaics (BIPV), Building Envelope, Building Form, Form Factor, Energy Performance

ÖZ

Bina formunun ve kabuğunun yüzeyleri, enerji performans değerlendirmesinde ve erken tasarım aşamasında bina entegre fotovoltaik (BIPV) konseptinin enerji potansiyeli için önemli bir rol oynamaktadır. Enerji verimliliği seviyesini artırmak için form faktörü (FF), yapının dışa açık yüzey alanları ile ısıtma / soğutma için gerekli enerji kullanım alanı (TFA) arasında güçlü bir ilişki sağlayan araç olarak önerilmektedir.

Bu araştırma, pasif ev standardına (PHS) göre spesifik birincil enerji talebini (SPED) karşılamak için enerji kullanım alanı (TFA) ile ihtiyaç duyulan bina entegre fotovoltaik (BIPV) alanı arasındaki ilgili dengeyi (korelasyonu) belirlemek amacıyla parametrik bir çalışma geliştirmeyi amaçlamıştır. Bu amaç doğrultusunda, dört modüler küpten elde edilen kare, dikdörtgen, L ve T gibi çeşitli form türleri aynı form faktörüne (FF) göre sınıflandırılmıştır. Her grup için uygun modüler form seçimi gerçekleştirilerek altı ayrı azimuta dışa açık yüzeyler için ayrı ayrı bina entegre fotovoltaik (BIPV) potansiyeli değerlendirilmiştir.

Sonrasında, cephe ve çatı kombinasyon önceliklerine göre kullanım faktörü ve kapsama endeksi senaryoları ile bina entegre fotovoltaik (BIPV) verimlilik düzeyi incelenmiştir.

Sonuçlara göre, üretilen enerji yeterliliğinin form konfigürasyonundan ve oryantasyonundan etkilendiğini göstermektedir. Ek olarak, 0,71'lik BIPV tabanlı form faktör (FF) değeri, daha az bina entegre fotovoltaik (BIPV) kullanımı için çatı tabanlı senaryoların önceliğini ifade eder. Son olarak, uygun formlar ve oryantasyon için toplam içeriğe göre bina entegre fotovoltaik (BIPV) kapsam endeksinin korelasyon değeri 0,92'den yüksektir ve bir değerlendirme modeli olarak farklı yerlerdeki diğer formlara genişletilebilir.

Anahtar Kelimeler: Bina Entegre Fotovoltaikler (BIPV), Form Faktörü, Enerji Kullanm Alanı, Enerji Performansı

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°	Degree
%	Percentage
A	Thermal Envelope Area [m^2]
A/GFA	Envelope Area to Ground Floor Area
A_{PV}	Photovoltaic Area [m^2]
a-Si	Amorphous Silicon
BIPV	Building Integrated Photovoltaics
C	Compactness [m^{-1}]
CI_{BIPV}	BIPV Coverage Index
c-Si	Crystalline Silicon
E	East
FF	Form Factor
FF_{BIPV}	BIPV-Based Form Factor
GFA	Ground Floor Area [m^2]
GHI	Global Horizontal Irradiance [kWh/m^2.day]
kWh/m2/yr	Kilowatt Hour Per Square Meter Per Year
kWp	Kilowatt Peak
m-Si	Multi-crystalline Silicon
mWp	Megawatt Peak
N	North
PHS	Passive House Standard
PR	Performance Ratio
PV	Photovoltaic

RC	Relative Compactness
S	South
S-15°	South Orientation-15° (165°)
S+15°	South Orientation+15° (195°)
SPED	Specific Total Primary Energy Demand [kWh/m^{2}a]
SY_{BIPV}	BIPV Solar Yield [kWh/m^2/yr]
TFA	Treated (Heated) Floor Area [m^2]
TPV	Thin Film PV
UF_{BIPV}	Utilization Factor for PV Integration into Envelope
V	Volume [m^3]
W	West
WWR	Window to Wall Ratio

Chapter 1

INTRODUCTION

1.1 Research Background

The history of Photovoltaic solar energy started in 1839 when Alexandre Edmond Becquerel discovered the photovoltaic (PV) effect via an electrode in a conductive solution exposed to light (an electrical current could be started in selenium solely by exposing it to light) and observed how the nature of certain materials turns light into energy and even published his findings (URL l). However, even after much research and development subsequent to the discovery, photovoltaic power continued to be very inefficient and solar cells were used mainly for the purposes of measuring light (URL 2).

The elegant Photovoltaic (PV) technology is being employed for solar energy conversion into direct current (D.C.) electricity without carbon dioxide emissions from its modular PV panels at different efficiency range of 7% to 40% -based on photovoltaic materials and number of cells composition-afterwards and then to convert it into alternative current (A.C.) electricity by the aid of inverters for general usage (Gaur et al., 2016) & (Ikkurti et al., 2015). Solar PV proficiency depends on local climatic conditions and solar radiation availability, module temperature, electrical traits of solar cells, etc. (Debbarma et al., 2017).

Building envelopes have opportunities for PV integration as BIPV (Building Integrated Photovoltaic) System to the exposed structure (Ritzenab et al., 2017) & (Li et al., 2015). BIPV systems started to become notable in late 1990's is the most promising solution to generate electricity and the elegant multi-functional building component concept which employs semiconductor PV modules solar energy to useful electricity and also for PV integration into the building envelope by replacement the conventional materials on roof, façade, windows and sun shading elements as well as to provide sun/weather (climatic) protection, thermal/acoustic insulation, carbon emission reduction of building footprint while power generation in responding building energy demand for utilization in the building itself, stored fed into the electricity grid, representing added value to the building (Shukla et al., 2016; Agrawal et al., 2010; Kim et al., 2017; Celik et al., 2015).

The construction element cost might be compensated by PV elements incorporated into the building to receive the significant saving in terms of mounting cost especially for components like brackets and rails. BIPV is considered as an amazing concept which promotes the architectural aesthetics, technical, economical, energetic, environmental aspects and social acceptance of the building as well. It must be noted that, in recent days, BIPV is considered as an economical viable technology thanks to its long operation for 25 years. The design principles of BIPV system is similar to PV system, with proper tilt angles based on location's latitude and orientation towards South in Northern hemisphere for maximum energy yield (performance) (Zomer et al., 2017). Its performance is impacted by increased temperature, less/non-ventilation in the building envelope, tilt angle and azimuth (Maturi et al., 2014).

It must be taken into account that challenges like partial shading, non-optimal tilt and azimuth deviations' is leading to performance ratio loss would impact performance ratio (PR). In terms of PV installation at partially shaded open areas, the non-uniform performance of PV generation under realistic situations is expected. Consequently, less solar radiation on shaded modules results power absorption and act as a load (Celik et al., 2013). However, shading effect on PV panels arising from building configuration or surrounded obstacles can be analyzed by appropriate simulation softwares including PVSyst and Design Builder.

Today BIPV roof systems are preferred more due to the less shadowing resulting more power supply while PV integration in facades become more and more popular for aesthetical issues (Osseweijer et al., 2017). Furthermore, the BIPV market share as roof-mounted and façade integrated technologies are 80% and 20% respectively (Krawietz, 2018). Also, based on the local climate, solar yield availability and mounting geometry, BIPV roof-mounted system output is applicable to cover 14.5% to 58% of the building energy demand (Zhang et al., 2018).

In addition, energy performance of the existed buildings, in terms of major renovation, must be promoted to satisfy the minimum requirement. In other words, the almost energy need is supplied on the building site itself by clean energy sources calculated on an annual basis (Chatzipanagi, 2016). So, it is expected, the BIPV application to accelerate in the coming years. Furthermore, key factors in BIPV system with high priority for integration are: architectural aesthetics, function, technology, cost and cost-benefit as well (Biyik, 2017).

From the other hand, there are two important factors of: compactness and form factor regarding energy demand and energy efficiency of the building form. The building form develops not just from consideration of urban design, function and form; it also depends on the local climatic conditions specific to the site and the energy benchmarks.

1.2 Problem Statement

Nowadays energy price is much higher than before and it is growing rapidly. Generally, building and their processes account for roughly one half of all energy consumption. Depending on the assumed climate, building scale and future development- providing needed energy such as: heating, cooling and electricity for their buildings are very important. But despite the huge amount of energy consumption in these buildings, there is less consideration for energy efficiency and utilizing effective solar energy in construction especially for electricity production onsite by friendly integrated elements called PV to meet their future needs.

Building integrated photovoltaics (BIPV) considered as the promising multi-functional active solar technologies offer cleaner energy production for energy efficiency and added value to the building. Hence, PV integration into the building envelope does not only becomes the unitized part of the building but also plays a prominent role in building shape formation and its geometric factors.

Also, there is a very strong correlation between ambient temperatures, availability of solar radiation and electricity demands. Consequently, due to the big available roof area in large scale buildings typically horizontal construction, these types of buildings represent an ideal application of building-integrated photovoltaic panels (BIPV) especially on roofs and facades for multiple energy advantages.

1.3 Aims and Objectives

This study aimed at finding the optimized area for photovoltaic installation in different building forms with the same 'form factor' and later integrating them in the buildings. Therefore, developing and validating a new approach for architectural-technical criteria’s to evaluate the energy efficiency and success level of PV integration in different types of buildings specially in the rooftop and South façade to achieve the most percentage electricity production but not only limited followed by:

- To discuss the existing approaches used and applied to assess the energy consumption of these buildings
- To identify the various opportunities of suitable surfaces on roofs/facades to harvest optimum solar radiation for PV integration
- To check the performance of BIPV in various form types of the buildings
- To present strategically energy production/efficiency with consideration to the architectural/energetic characteristics for PV integration in buildings by the aid of simulation softwares.

1.4 Research Method and Materials

This research is based on collected data regarding solar energy, climate and other related materials from different sources including: journals, books, websites, reports and case studies. From the other hand, due to the complexity of the subjects, the new approach is employed to find the relationship between the energy demand of functional floor area and the needed area on the solar envelope to meet the requirements according to the Passive House Standard. Thereafter, by synthesizing these parts and simulation by the aid of PV softwares and related literature review by qualitative and quantitative approach for BIPV approach development through the prototype modelling which is followed by applying new BIPV approach on various form types to find out the optimized BIPV regarding form shape characteristics. The best form type for BIPV application will include the highest PV solar yield to meet its specific primary energy demand. The aim of the proposed approach is to establish the relationship between the FF and the performance of PV panels by means of well-organized building forms with the same volume, established in various configurations, and analyzed in different orientations with different C, to meet annual energy demand based on the international Passive House standard (PHS).

1.5 Research Limitations

Due to the complexity of finding the suitable area for PV integration on building envelope in one hand, and various parameters for energy loss through exposed surfaces of the building form type, four modular cubes selected as the basis to create various form types of shape configuration to arrange them based on the Passive House Standard (PHS) which identifies the 120 kWh/m^2 as annual specific energy demand (Truonga and Garvieb, 2017).

Also, it is assumed that the prototype form and case study form types are located in the northern hemisphere and the cool temperate climate of Tabriz city, Iran, at a latitude and longitude of 38.13° N and 46.28° E, respectively. All of the form types have the same double-glazed windows in all orientations,

Chapter 2

PV TECHNOLOGY AND ITS ADAPTABILITY IN BUILDINGS

2.1 Photovoltaics (PV) as Contemporary Solar Technology

2.1.1 Basic Principles of PV Cell

Nowadays, solar power is considered the most dependable source of providing electricity in the globe. Photovoltaic [PV, photo=light, voltaic=electricity] module consists of solar cell used to take sunlight and transform it into electricity. This electricity is used in buildings, public electricity system, or it can also be used in batteries. Silicon cell (a semiconductor) is most often used in solar cells for conducting electricity. And silicon cells are doped with boron to make a p-type semiconductor. Besides, on doping with Phosphorus, silicon forms the n-type semiconductor. The photovoltaic effect is a phenomenon that occurs when the light is cast to the cell, then the generation of electrical charge begins, and this is when the flow is directed through the load (see figures 2.1, 2.2).

The light going through the cell produces a voltage that exists inside two layers, which finally emerges at the terminal. Thus, electricity increases both with cell area and light intensity. Furthermore, the rate of voltage is related to the kind of materials. As much as 0.5 V is generated by a single silicon cell, no matter how big the cell is (Sick, 1996).

Controlled circumstances are required to measure photovoltaic cells efficiency (i.e., a cell temperature of 25° C for a solar radiation *of* 1000W/m^2 and an air mass of 1.5), despite the fact that the nominal operating cell temperature (NOCT) is, in fact, a lot more than a temperature of 25° C. The main reason for low efficiency as well as low electrical output in a photovoltaic module is a high level of NOCT (Ibrahim et al., 2007).

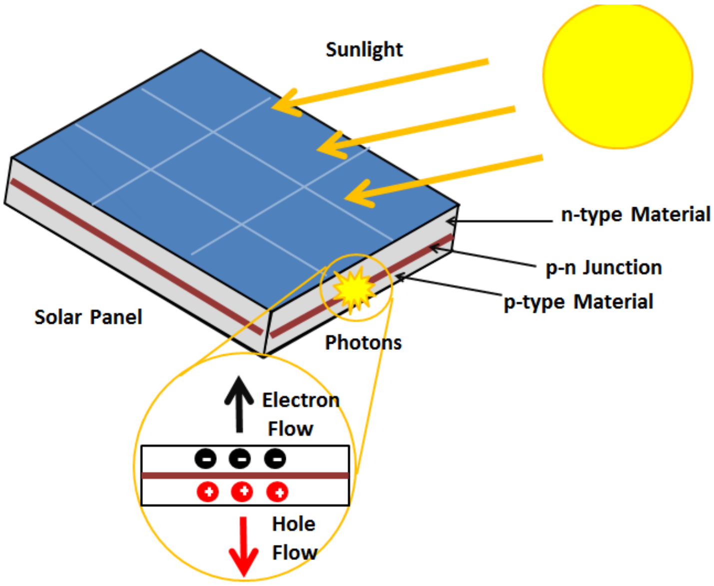


Figure 2.1: Photovoltaic Effect (URL 1)

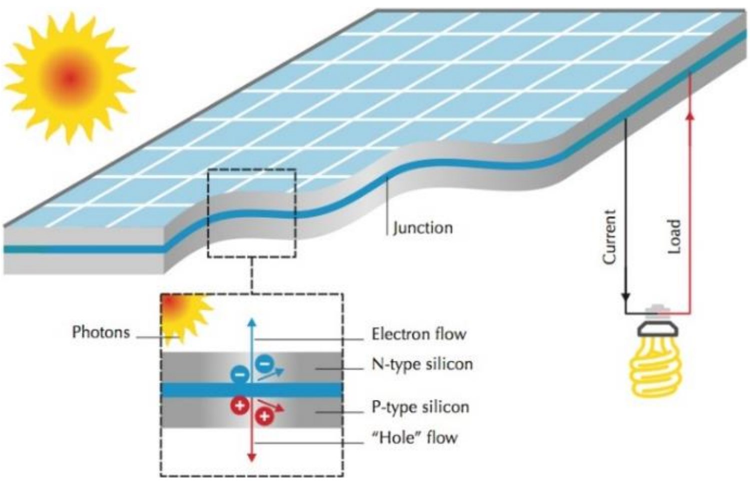


Figure 2.2: Schematic Function of the PV Cell (URL 2)

2.1.2 Historical Development of PV Cell

Becquerel effect also referred to as the “photovoltaic effect”, was developed by a French experimental physicist, Alexandre-Edmond Becquerel (1820-1891). In an attempt to generate electricity effect, Becquerel (1839) carried out an experiment in which silver chloride was placed in an acidic solution and exposed it to light while it was connected to platinum electrodes.

Semiconductors have been the main elements in photovoltaic technology ever since. Then, in 1953, the new silicon solar cell was discovered by the three scientists Daryl Chapin, Calvin Fuller and Gerald Pearson working at Bell Laboratories. The scientists conducted experiments with impurities changing silicon, using both very poor and very good conductors. They made cells by dipping gallium-rich silicon into a hot lithium bath and illuminated it with a lamp, extracting a negative charge from silicon, developing silicon wafer whose conversion efficiency was 6%. And this is how the solar cell was developed.

The first use of solar cells was to power satellites. Dr. Elliot Berman was the first to develop a solar cell much cheaper than the previous one. He used poor quality silicon and other materials in the 1970s. Thus, he decreased the price to 20 $, whereas it used to be 100$ per watt. This proved that it is possible to use cheaper PV materials and that PV materials have good power capacity. Therefore, mass production of PV material, as well as testing and science research of the photovoltaic materials, began.

Thereupon, the PV array efficiency will be lower compared to rated panel efficiency, and the latter is also lower compared to rated cell efficiency.

Besides, crystalline systems based on silicon are susceptible to cell temperature; if the temperature is above 25 °C, output decreases by 0.5 %. When dust and dirt accumulate on PV module, array output results in more loss. (Mani and Pillai, 2010). Nevertheless, the efficiencies that manufacturers believe exists there, is not seen on the field. In addition to the losses in the system itself which is related to the inverter, climatic factors (solar irradiance features, wind speed, and ambient temperature) and the factors pertaining to installation site (latitude, positioning, dust, the rate of pollution and tree cover) have an effect on PV systems functioning. Table 2.1 presents the historical development for PV solar cells which is started by Edmond Bequerel as photovoltaic effect.

PV cells are joined to PV modules in order to enhance power output. A PV panel along with an optimum voltage and current at the inverter output is made up of some PV modules. The modules are *assembled into arrays,* which are what the *large PV panels* are *called.*

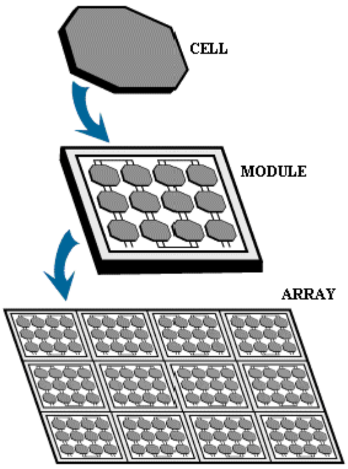
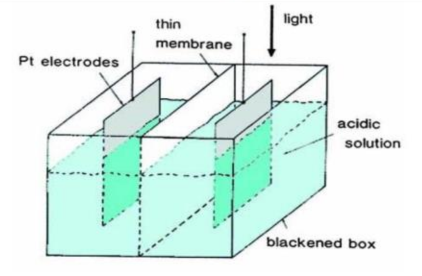
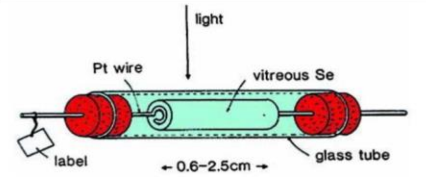
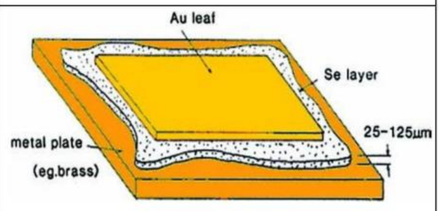
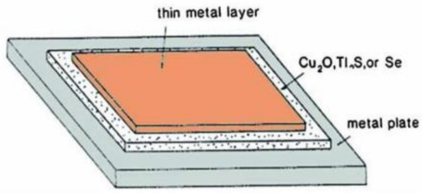
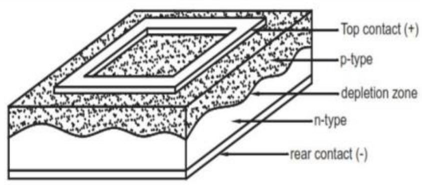
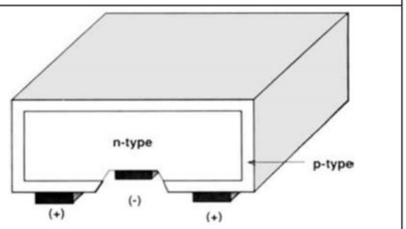
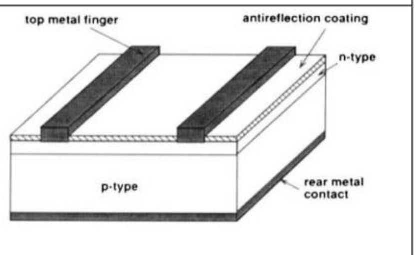


Figure 2.3: From Solar Cell to Array (URL 3)

Table 2.1: Historical Developments of PV (Adopted from Agrawal & Tiwari, 2011)

Date	System	Description	Solar cell apparatus
1839 1883	Edmond Bequerel apparatus	- photovoltaic effect between two platinum electrodes coated with either silver chloride or silver bromide inserted into an acidic solution	
1876	Adams and Day apparatus	- photoconductive effect in a selenium bar merely by the action of light	
1883	Thin-film selenium by Fritts	- First true solar cell - Using junctions formed by coating the semiconductor selenium with an ultrathin, nearly transparent, gold layer - solar cell efficiency < 1%	
1930	Structure of the photovoltaic devices by Bergmann	-Employing both the selenium cell and the copper oxide cell in light-sensitive devices such as photometers for use in photography - solar cell efficiency < 1%	
1941	Silicon solar cell by Ohl	- the first semi-conductor p–n junction solar cell - Bases for the most PV systems (silicon p–n junctions) produced to date	
1954	The first silicon cell by Chapin, Fuller and Pearson	-The first monocrystalline silicon solar cell -6%<stabilized efficiency<10%	
1960	Silicon cell design developed for use in space	-Silicon cell design developed for use in space - Solar cell development - energy efficiency< 14% under terrestrial sunlight	

2.1.3 Typology of PV Cell

Today, it is emphasized that solar cell is not only a growing technology, but it is also one of the fastest developing products in the industries related to renewable energy (Sick, 1996). In general, PV technology is mainly divided into two groups: crystalline and thin film. The size of a common crystalline cell may be 100*100mm. modules are formed the combination of some cells. In theory, maximum efficiencies the silicon can have are about 30%. In practice, this rate is improving. Copper indium diselenide (CIS) and cadmium telluride (CdTe), are now provided. Another new way to enhance efficiency includes developing multi-junction cells that implement solar spectrum extensively.

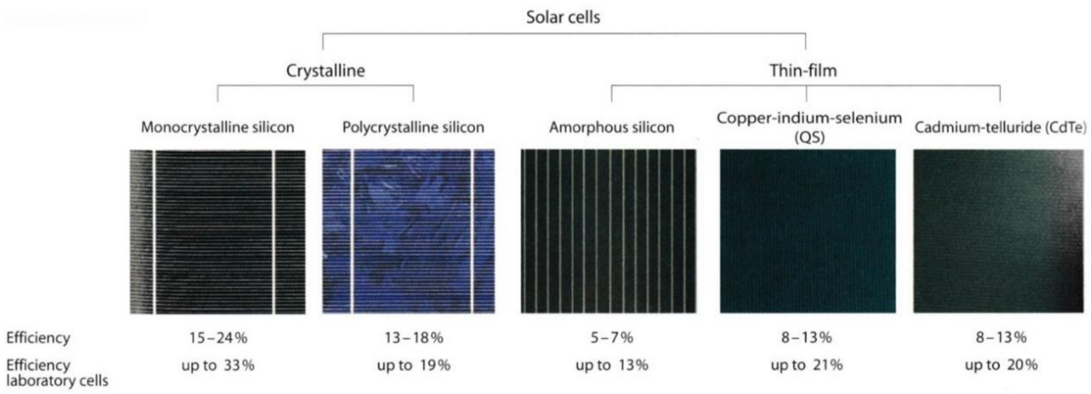


Figure 2.4: Comparing PV Cells (Hegger et al., 2016)

Cell type	Max. cell efficiency (lab.) [%]	Module efficiency (commercial) [%]	Output per m^2 of module area [W_p]	Space needed for 1 kW_p [m^2]	Loss of output due to temp. rise [%/°C]
Monocrystalline, standard	21.6	12–16	120–160	6.5–9	0.4–0.5
high-efficiency cells	24.7	16–20	160–200	5–6.5	0.3–0.4
hybrid HIT cells	20.2	16–17	160–170	6–6.5	0.33
Polycrystalline	20.3	11.5–15	115–150	7–9	0.4–0.5
Silicon, amorphous	13.2	5–7	50–70	15–21	0.1–0.2
microcrystalline	15.2	5–7	50–70	15–21	0.5–0.7
micromorphous	13.0	7–9	70–90	11–14	0.3–0.4
CIS, standard (selenium)	20.0	8–11	80–110	9–13	0.3–0.4
sulphur	13.1	6–7	60–70	15–17	0.3
nano solar cells	14.0	8–10	80–100	10–13	
CdTe	16.5	6–11	60–110	9–17	0.2–0.3

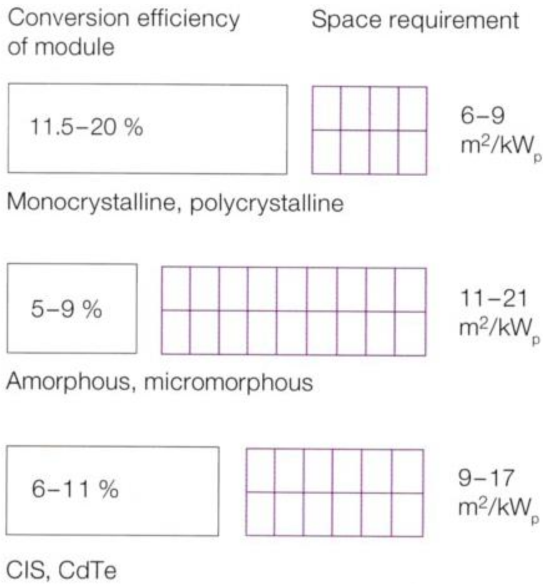


Figure 2.5: Conversion Efficiencies for Different Cell Types, Needed Space and Performance (Weller et al., 2010)

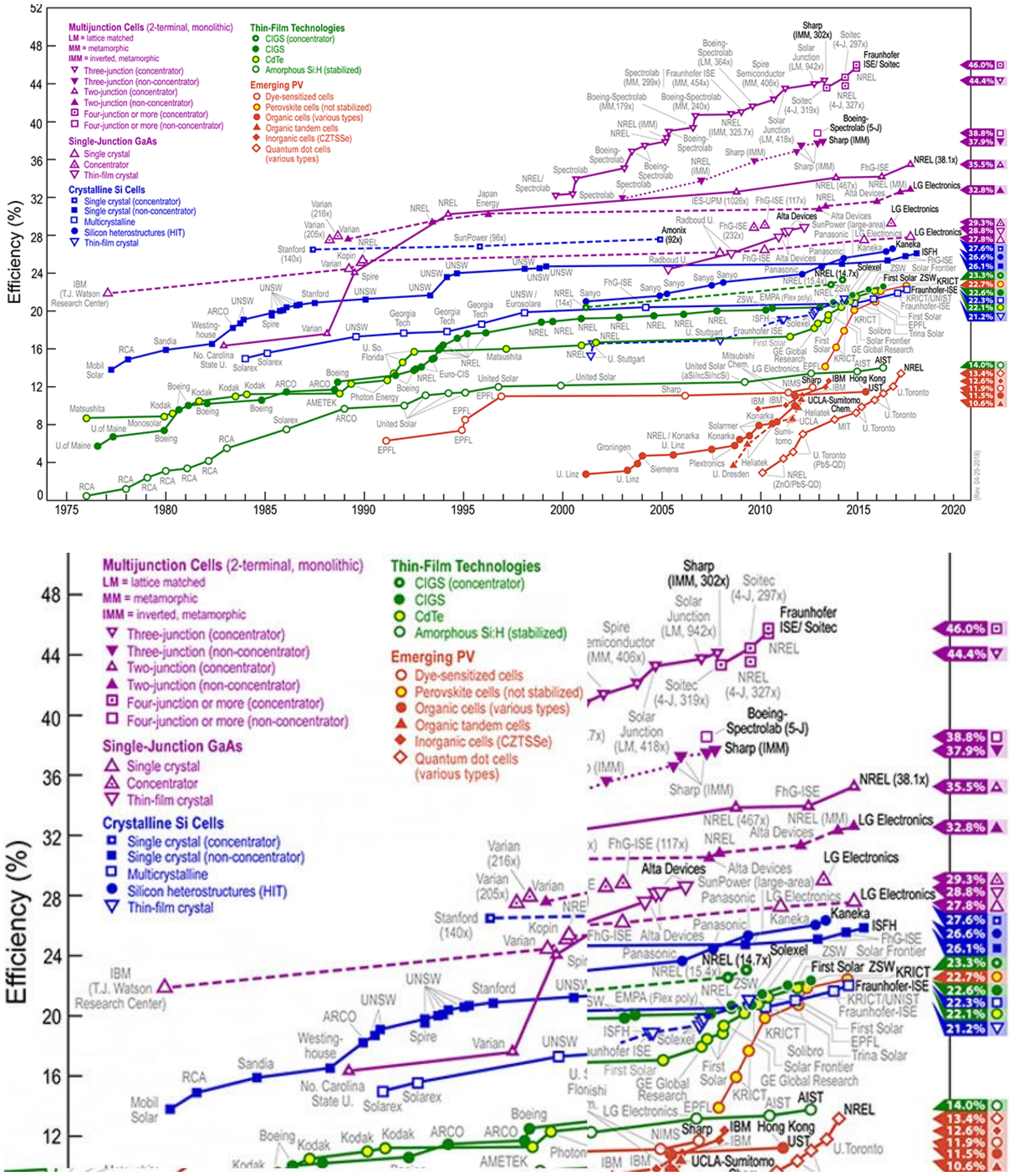


Figure 2.6: Timeline for Cell Efficiency Records within Different Families of Semiconductors (Up) and Zoom-in for the Recent Years (Down) (URL 4)

2.1.4 Form and Color of PV Cell

The color of solar cells is usually blue, dark blue or even black, though they can have other colors like grey, green, red, orange and yellow, which are not normally standard. Moreover, they can be much more expensive than standard ones. Highest efficiency belongs to blue-colored cells.

Color is affected by the type of module. Frameless modules make it possible for the roof to appear as unicolor since the roof is not disturbed by the frame that might have more different colors or even material than that of the cells. The whole surface color is, in fact, the color of the roof.

Framed modules may have another visual impression. The frames that seem heavy greatly affect the general visual impression of the PV array as well as its combination with the building. Smaller frames having the same color as the cells are not visible at the surface. Sometimes the frames are used to give a particular impression. Framed modules have an effect on the dimensions of modules and, as a result, the mounting profile will be affected. If the frame and encapsulant colors at the module's rear surface are different, more opportunity will be available for design interest (Prasad & Snow, 2010)

2.1.5 Technology Generation Development of Photovoltaics

PV technologies are mainly classified into two big groups: PV based on the wafer (also referred to as the first-generation PV) and PV with the thin-film cell. Generally, the development for the PV technology generations is categorized in three groups as presented in figure 2.7.

Traditional crystalline silicon (c-Si) cells and gallium arsenide (GaAs) cells are all examples of wafer-based PVs. Except for c-Si cells, GaAs has the highest efficiency among solar technologies having different single-junction, with c-Si being the most dominant in the PV market nowadays (about 90% market share).

The intake of light in thin-film cells is usually 10-100 times more efficient than silicon, making it possible to use a few microns thick films. Also, Cadmium telluride (CdTe) technology found its way on the market, with a cell efficiency of more than 20% and a module efficiency of 17.5%. CdTe cells have almost a 5% share of the overall market. Other thin-film technologies available on the market include hydrogenated amorphous silicon (a-Si:H) and copper indium gallium (di)selenide (CIGS) cells, which have a 2% share of the market. Another development is the technology of copper zinc tin sulfide existing for years; however, it still needs some time for actual commercialization (URL 5).

The 3rd generation PVs include thin-film PVs, which are the PVs that use technologies in which it is possible to overcome Shockley limit, or are based on new semiconductors. DSSC, organic photovoltaic (OPV), quantum dot (QD) PV and perovskite PV are present in 3rd generation PVs. The efficiencies of the cells of perovskite and commercialized 2nd generation technologies like CdTe and CIGS are almost the same. Other new PV technologies are still like cell efficiencies which are less than 15%.

Perovskite solar cells have advantages other than high and increasing efficiencies and low cost of material & processing. Some other characteristics of perovskite solar cells including flexibility, thin-film, semi-transparency, tailored form factors, light-weight are among the value propositions of this technology.

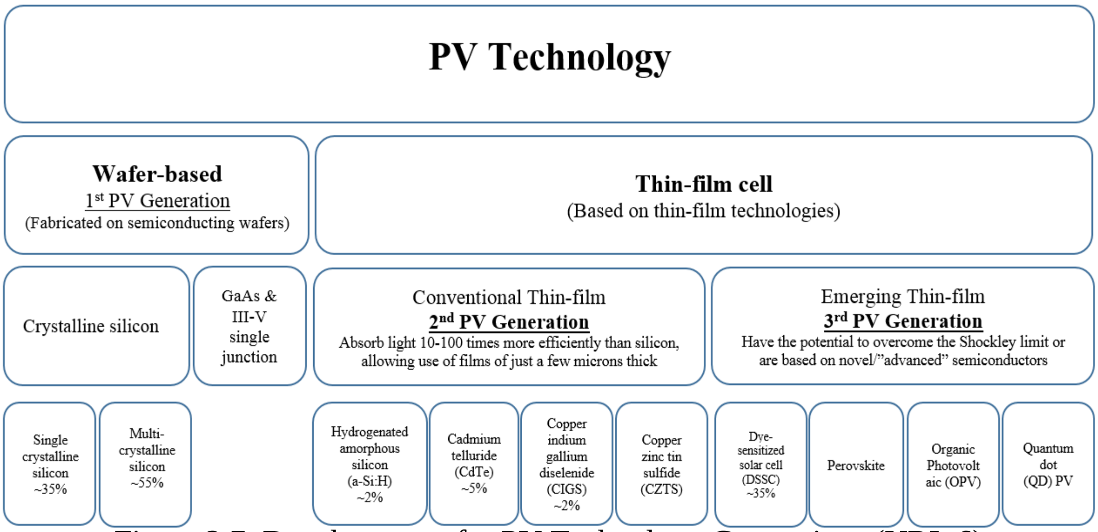


Figure 2.7: Developments for PV Technology Generations (URL 6)

2.1.5.1 Crystalline Silicon (c-Si) Cells

The first-generation cell, which is also called Crystalline solar cells is a bulk sort of solar cell. And it is formed of the traditional phosphorus boron doped silicon semiconductor. PV elements, in c-Si, are developed via interconnection of conventional Si wafers, the major advantage of which is its high reliability when used for decades as well as its high efficiency power conversion.

Employing c-Si cells for BIPV facilities makes advantages of more power generation for the fixed floor area than other technologies. Also, the anti-reflection coverage thickness specifies its color effect.

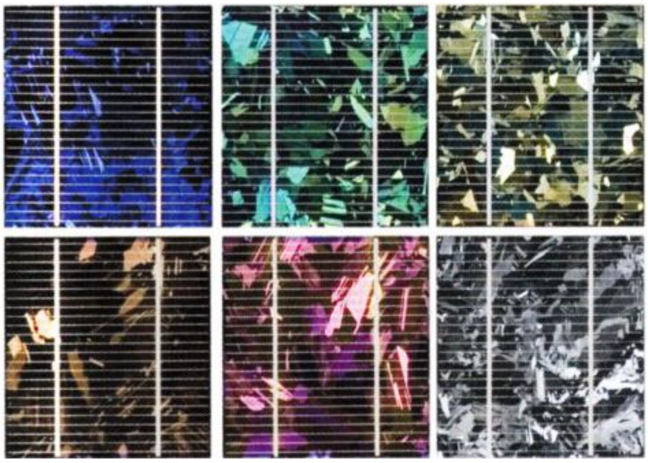


Figure 2.8: The Effect of Coating Thickness on the Color Appearance in Crystalline Cells (Weller et al., 2010)

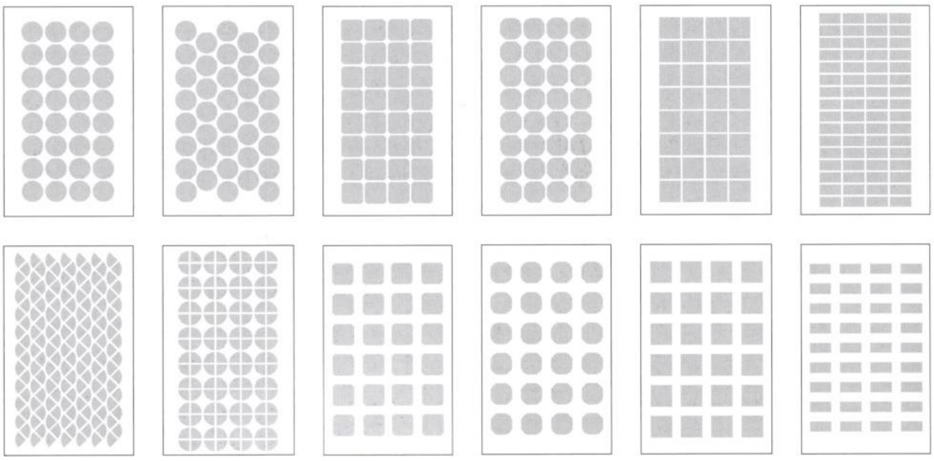


Figure 2.9: Different Cell Arrangement with Regular-Pattern (Weller et al., 2010)

Based on these characteristics, the approach of integrating PV technology into the materials used in construction is determined by choosing a certain group and as a result finalized aspects. Nowadays, the range of electricity conversion-efficiency in silicon solar module existing on the market is 12–18%. Over 80% of solar energy received is reflected or turns into heat energy. There is a remarkable increase in the temperature of the cells following long-lasting operations; therefore, cell efficiency decreases noticeably. Electricity yield is improved once the PV module is cooled with a flow of water or air. Meanwhile, it is possible to use this heat released by air or water flow for space heating or hot water systems.

2.1.5.1.1 Mono-Crystalline Silicon (m-cSi)

Having the maximum conversion efficiency, monocrystalline silicon PV cells are the first type of photovoltaic cells. These solar cells have the highest price among the others. Very pure semiconductor materials are required in the production of these cells. The cells are cut in thin forms out of a highly purified silicon cylinder, and such a approach leads to high performance. Cell color of monocrystalline is either blue or black.

The main use of monocrystalline solar cells is when space is considered as a constraint and high output is required. The color of a monocrystalline panel is usually either black or iridescent blue. High efficiency is the major advantage of these cells, whose cell dimension, cell efficiency and module efficiency are 12.5 cm, 22.5%, and around 15% (13% to 19%), respectively. Despite the fact that the process to develop monocrystalline is complicated, its cost is marginally higher compared to other technologies.

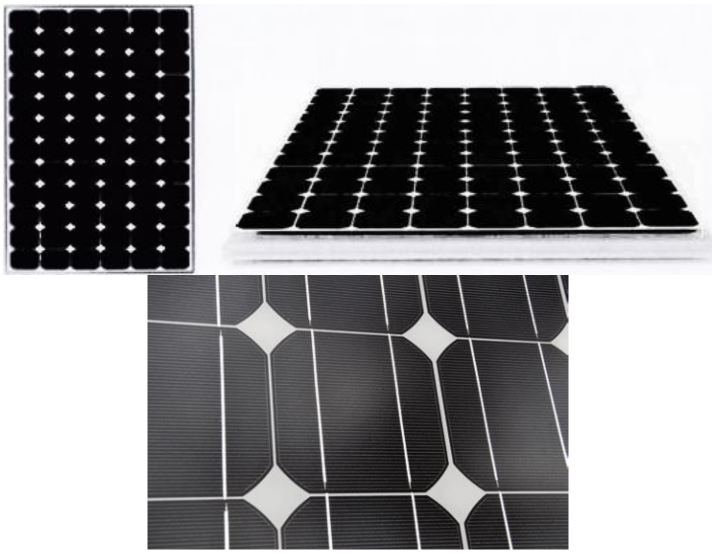


Figure 2.10: Mono-Crystalline Silicon Cells (Hootman, 2013)

2.1.5.1.2 Poly-Crystalline Silicon (mc-Si)

Silicon ingot having materials with high purity is used in the production of polycrystalline cells. Its metal flake is visible, and a set of the strap for sunlight. First, polycrystalline cells, also called multi-crystalline cells are poured into a cuboid molten shape rather than a single crystal, and after being melted, they are poured into a mold. Then, this square shape is cut into thin square wafers having lower materials. Therefore, producing polycrystalline silicon becomes easier and also cheaper compared to monocrystalline cells. In addition, because of grain boundaries, efficiency is lower.

Manufacturing of multi-crystalline silicon cells is cheaper than mono-crystalline because the production process is simpler. The dimension of the cells is 21*21 cm; however, efficiency is low, typically around 12% under normal circumstances. This means that in normal conditions if the panel size is 1 m^2, it can produce 120W to 125W electricity; however, there is an increase in efficiency up to 20.4% (URL 5). Cell colors look different from a single cell, appearing in lots of variations of blue.

In new techniques, the polycrystalline film is used on a cheap substrate. The substrate like this has metallurgical-grade silicon sheet, stainless steel, ceramics, and quartz glass, in which several growth techniques are used to put silicon films on these substrates.

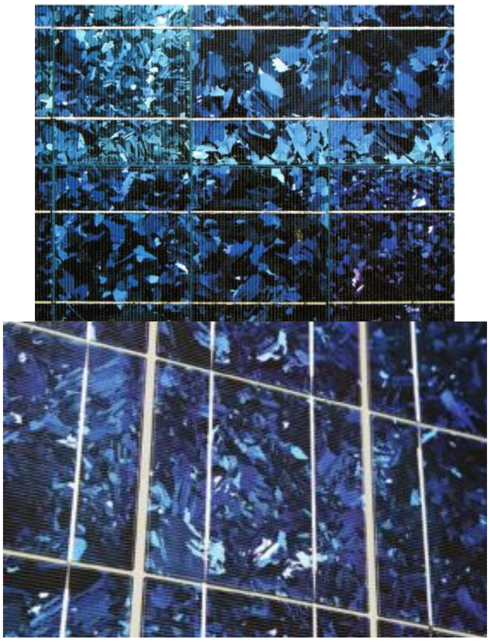


Figure 2.11: Color Appearance of Poly c-Si Cell (Hootman, 2013)

2.1.5.2 Thin Film Solar Cell (TFSC)

Thin-film technology is considered the most remarkable photovoltaic technology in the field of renewable energy. The main use of thin-film technology is in the architecture of a building.

Thin film solar cells (TFSC) are built via placing thin silicon layers having PV materials (cadmium telluride, copper indium selenide/sulfide, amorphous silicon) over a superstrate which means that this layer is covered on the side facing the sun or PV module's front side. This protects PV materials from the environmental impact like degradation, but at the same time makes it possible for the solar spectrum be transmitted in full length.

The outcome in the process mentioned above is a thin flat glass or flexible PV materials (Paridaa et. al., 2011). However, the efficiency of energy conversion is around 12% to 20%. This is lower than crystalline cells as less silicon is used here. Since it is possible that at times higher temperatures disturb system functions, efficiency does not always play a pivotal role. As these technologies develop every day, efficiency levels increase too. Since thin-film technology has some features that make its architectural design attractive such as flexible module, different light intensity, low-cost materials, there will be more demand for this technology, and it will be a rival for crystalline silicon. Some of the major advantages include: lower thickness, high rate of integration possibility, having flexibility with regard to geometry and dimension, PV materials can be placed on various materials (flexible metal, glass or polymer).

Figure 2.12: Various Kinds of Thin-Film Cells (Hootman, 2013)

2.1.5.2.1 Amorphous Silicon (a-Si)

The amorphous silicon does not have to contain the arrangement of crystal structures, and its main feature is a layer of thin semiconductor (thin film). Instead of a crystal structure, silicon atoms form amorphous silicon cells in homogeneous thin layers. These cells are made up of several a-Si layers (usually< 1µm) which are plastic or glass substrates, that is why a-Si is also called thin-film PV technology.

The efficiency of amorphous cells is, nevertheless, less than crystalline cells. Their efficiency is around 6%. However, its manufacturing technology is the most popular among TFSC as it requires low materials, cost, and process temperature. Furthermore, payback time is short; it is nontoxic with flexibility, and a substrate is cheaper like float plastics or glass.

As their cost is very low, they are really suitable for many applications in which high efficiency does not matter, but low cost is required. When amorphous silicon was first studied, it was known that plasma-deposited amorphous silicon had a substantial amount of hydrogen atoms which were bonded into the amorphous silicon structure. Amorphous silicon is usually referred to as “hydrogenated amorphous silicon (a-Si:H)”.

Advantages of a-Si:H comparing c-Si are as following:

- The simple and non-expensive technology
- The ability for much more light absorption (because of the exposed coating) than c-Si (approximately 2.5 times) for the same thickness layer
- Less energy consumption for the manufacturing process in comparison with c-Si
- Less material utilization for a-Si:H thin film production, less cost (one-third than mono/poly c-Si) and cheaper as well
- The deposition possibility for different types of substrates containing: fold-away, flexible and bent forms
- General efficiency improvement is continued, albeit its low rate of 10% comparing c-Si
- Less influence on panel efficiency regarding shading effect and high temperatures

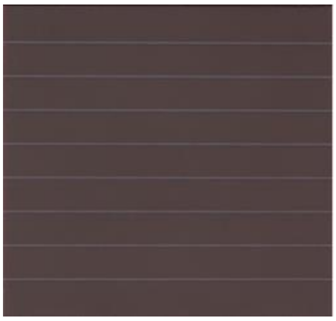


Figure 2.13: Amorphous Silicon (a-Si) type (URL6)

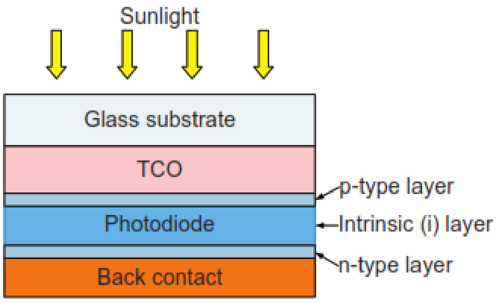


Figure 2.14: Different Layers of Hydrogenated Amorphous Silicon (a-Si:H) Designed on Gass Layer (Agrawal & Tiwari, 2011)

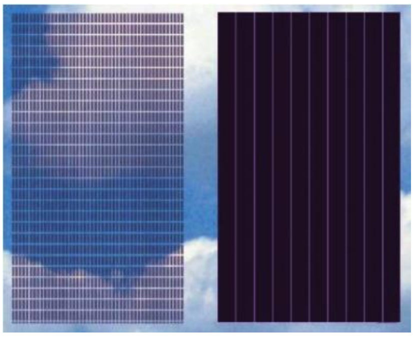


Figure 2.15: Different Types of Thin-Film Module: Semi-Transparent (Left), Opaque a-Si (Right) (Heinstein et al., 2013)

2.1.5.2.2 Other Thin Films

Nowadays, other materials like copper indium diselenide (CIS), and cadmium telluride (CdTe) are used in PV modules. These types of technologies seem interesting because they are produced using processes costing lower than those of crystalline silicon technologies, and they have module efficiencies higher than a-Si. However, some raw materials are not as available as silicon. Also, as some special elements are used, there is the risk of environmental toxicity, though it is possible to remove these problems through careful manufacturing, disposal and recycling processes.

2.1.5.2.3 Dye-Sensitized Cell (DSC)

The technology of dye-sensitized Solar Cell (DSC) is actually considered as artificial photosynthesis, which performs well when radiation is indirect; it is cloudy; and when Gratzel titanium dioxide (TiO2) cell has dominated marginally-shaded DSC technology temporarily or permanently. Photosensitive dye covers titanium dioxide particles which are placed between electrodes in a solution that contains iodine ions. Once the light is cast to this dye, some of the electrons jump to the particles of titanium dioxide, and then one of the electrodes attract these electrons. Meanwhile, electrons are transported back from the other electrodes through iodine ions in order to recharge dye particles. Such action causes electrons to flow around the circuit. Technically, efficiencies can as high as 10 percent or even more with the passing of time. And they perform well under various sunlight conditions.

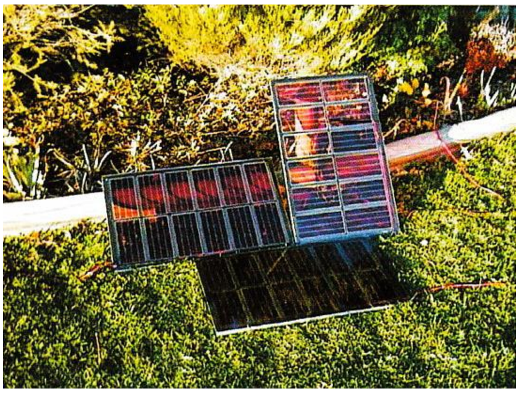


Figure 2.16: Titanium Dioxide (TiO_2) Cell (Prasad et al., 2005)

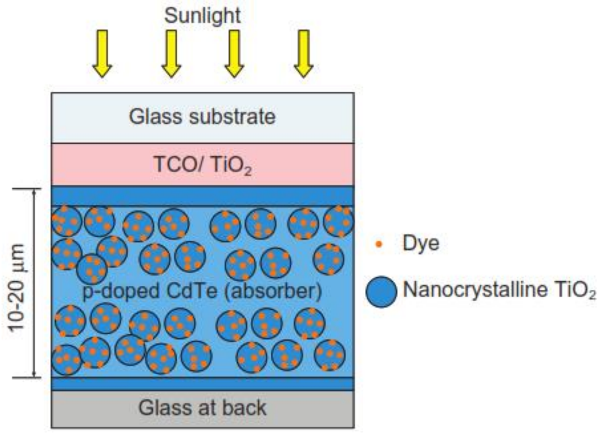


Figure 2.17: Different Substrates of Dye-Sensitized Solar Cell (Agrawal & Tiwari, 2011)

2.1.5.2.4 Polycrystalline Thin-Film Photovoltaics

2.1.5.2.4.1 Cadmium Telluride (CdTe)

Cadmium telluride-based (CdTe) PV solar cells have the highest share pertaining to the production of thin-film module on the market. Compound cadmium telluride (CdTe) is used in this cell, which acts as a semiconductor converting light into direct current. A CaTe cell has optical and chemical features required in the absorption coefficient, which is around 105 per cm whenever the region is visible. This means that such layers with a thickness of few micrometers have the ability to absorb around 90% of the incident photon. Their energy band gap is 1.5 eV (URL7).

New semiconductors have yields which are higher compared to presently diffused ones. Appropriate payback time of energy and lower expenses in production are advantages of this technology. The disadvantages of this technology are the same as the previously mentioned ones: indium (In) and small amounts of toxic materials (cadmium) in production are available.

The quick manufacturing of CaTe cells, as well as lower costs compared to technologies based on conventional silicon, makes them the most desirable PV cells on the market worldwide after the most common crystalline silicon cells.

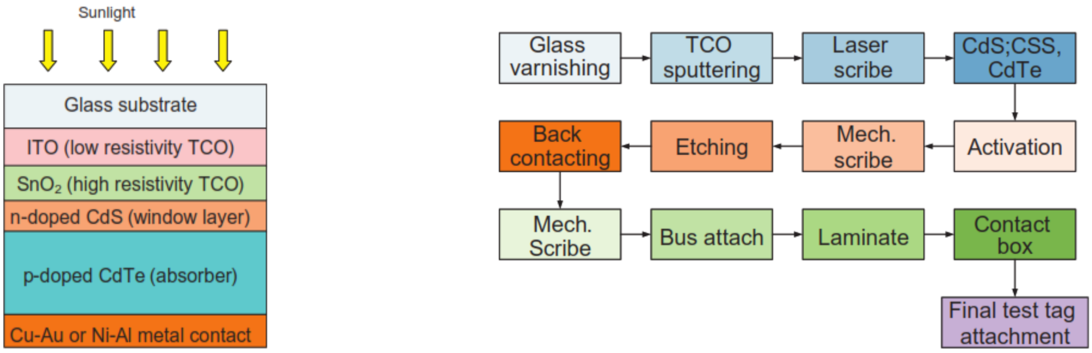


Figure 2.18: Structure (Left) and Production Phases (Right) of the CdS/CdTe Solar Cell (Agrawal & Tiwari, 2011)

A typical CdTe superstrate having thin-film PV is shown in this figure. Here, the layers forming the device are placed over a glass superstrate making it possible for the sunlight to go through. The sunlight enters the glass, generating electrical current as well as voltage in the layers beneath. The cell efficiency recorded for CdTe device in the world is over 22% (URL7).

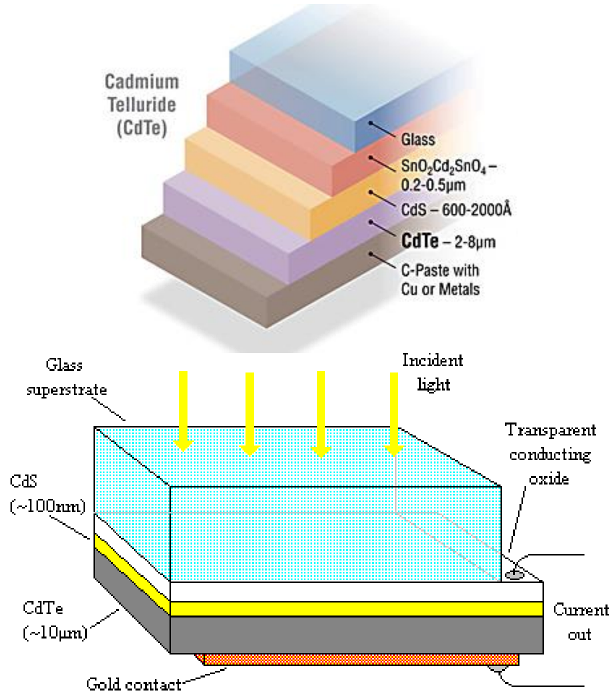


Figure 2.19: Function and Specifications of Conventional Cadmium Telluride (CdTe) (URL 7, 8)

2.1.5.2.4.2 Copper Indium Gallium Dieselnide (CIGS)

The efficiency of Copper Indium Gallium Diselenide (CIGS) or Copper indium diselenide (CIS) cells is higher compared to amorphous silicon. And also, their long-lasting stable quality, the flexibility of solar cells, which are produced by steel foil and Polyimide is used in roofs and materials of façade.

Copper Indium gallium Dieseline CIGS cells absorb 99 percent of light before it reaches 1µm into the cells, so these cells have the ability to absorb the most amount of light. The market of this technology is growing very fast. This technology has two main disadvantages. First indium (In) is not as available as other materials and cadmium (Cd) and some toxic materials exist in the production process. The structure and composition of these layers have the ability to store sunlight charges long enough that it is possible to separate and collect them on both sides. Solar cell components which are based on CIGS thin-film have the highest efficiency for large-scale cells as well as commercial thin-film cells. The efficiency of single-junction for small areas reaches 22%; however, the rate of module efficiency is 16%, as different companies have also verified this (URL 9). The following figure indicates a common CIGS substrate thin-film of a photovoltaic device. Here, the layers are placed over a substrate of metal, glass or polymer. Sunlight penetrates through the upper layer (transparent oxide) generating voltage and electrical current in the layers beneath (see figure 2.20).

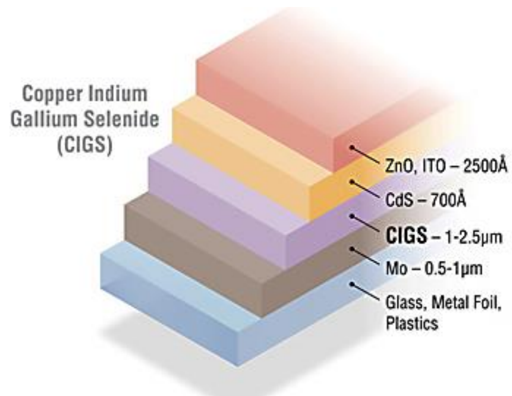


Figure 2.20: Structure of the Copper Indium Gallium Selenide (CIGS) Solar Cell (URL9)

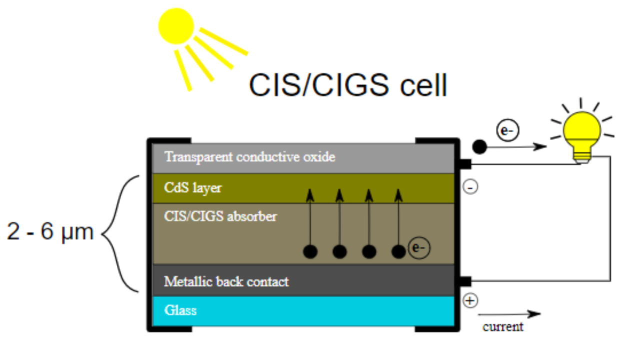


Figure 2.21: Copper Indium Selenide (CIS) and Copper Indium Gallium diSelenide (CIGS) Solar Cell (URL 10)

2.1.5.2.5 Perovskite and Organic PV

2.1.5.2.5.1 Perovskite Solar Cells

As light absorption, the mobility of charge-carrier, and a lifetime of the materials is excellent, working with solar cells in which perovskite materials are used has progressed fast, which in turn, has led to the high efficiency of the device, potentially low-cost, and industry-scalable industry. In order to achieve low-cost and scalability, some barriers concerning stability and compatibility in the environment should be overcome. However, if such concerns are to be addressed, Perovskite-based technology has the potential for rapid development of large-scale solar energy. The features of basic materials have attracted attention in the use of hybrid perovskite semiconductors in various energy applications beyond traditional electronic or optica systems (URL 11).

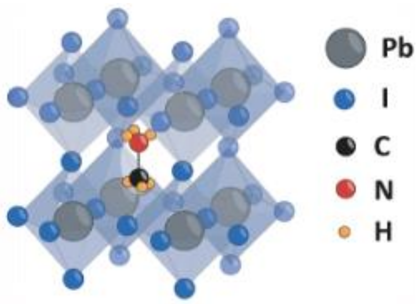


Figure 2.22: Methyl Ammonium Lead Triiodide (CH3NH3) PbI3, or MAPbI3 as Typical Perovskites (URL 11)

2.1.5.2.5.2 Organic Photovoltaic Solar Cells (OPV)

Organic Photovoltaic solar cells (OPV) are another fast-developing PV technology, whose cell efficiency is promising (around 13.2 presently); its initial lifetime is (>5,000 hours unencapsulated), and it has the potential in processes of roll-to-roll manufacturing. OPV can be used in the markets of building-integrated PV since they are available in various colors, and can be used efficiently in transparent devices (URL 8). Furthermore, OPV development is along with developments of materials, process, and deposition of materials, and making devices under controlled pressure and temperature conditions (see figures 2.23, 2.24) (URL 12).

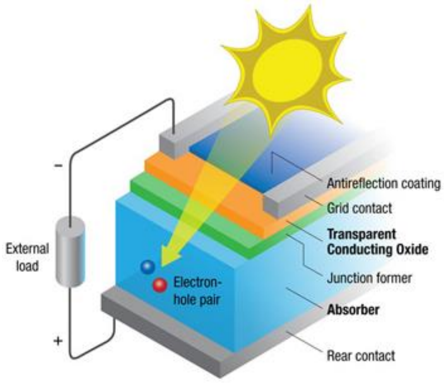


Figure 2.23: OPV Details (URL 12)

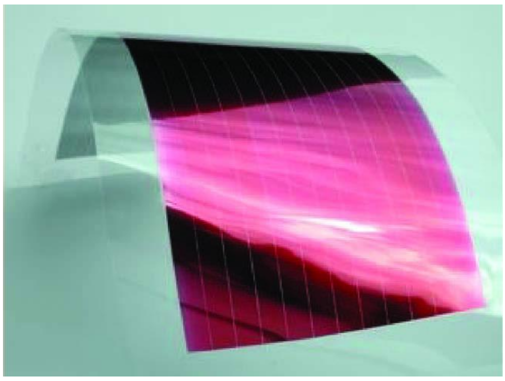


Figure 2.24: Flexible Layer-Based OPV (Heinstein et al., 2013)

Figure 2.25 shows efficiency improvement in various kinds of photovoltaic technology. While advances are seen in all variations, some advances are even more noticeable.

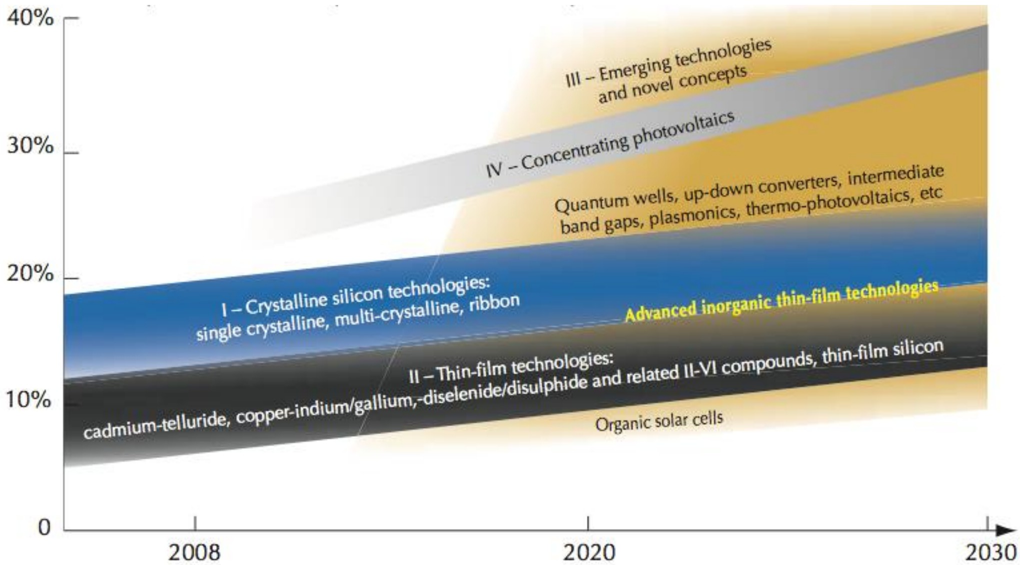


Figure 2.25: PV Global Market and Comparison of the Module Efficiency Rate) (URL 13)

2.1.6 Advanced PV Technologies

2.1.6.1 Multi-Junction Solar Cells

Multiple junctions are used by multi-junction cells (a single n-type to the p-type junction is used by conventional cells).

As a result, higher efficiency is allowed for broader sunlight spectrum is converted into energy (Hootman, 2013). Several semiconductor layers having various energy gaps are used in these types of cells for increasing the general cell efficiency. Hence, photons of a specific energy range are absorbed optimally by each layer.

2.1.6.2 Heterojunction Solar Cells

A layer of amorphous silicon thin film is placed over a crystalline silicon wafer, and its efficiency improves. The hybrid approach has as much efficiency as crystalline cells, and at the same time maintains some advantages of a thin film such as having higher efficiencies in high temperatures and lower light. Bifacial modules have the ability to generate electricity as light strikes the module both from front and back faces (Hootman, 2013).

2.1.6.3 Photovoltaic/Thermal Hybrids (PV/T)

Photovoltaic and thermal hybrids (PV/T) integrate solar cells and thermal collectors into one module that generates electricity as well as heat. Using this solar thermal collector in the module, waste heat is captured from the photovoltaic process (Hootman, 2013).

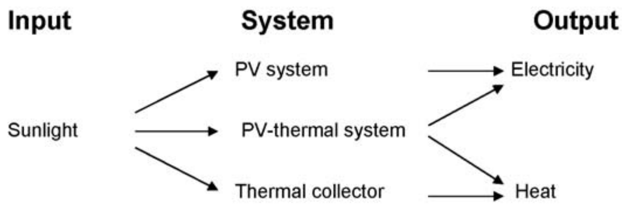


Figure 2.26: Comparison Among Different Solar Systems of PV, PV/T and Thermal (Author, 2021)

2.1.6.4 Concentrating Photovoltaics (CPV)

Increasing solar insolation that strikes solar cell is another approach to enhance module efficiency. One of the features of concentrating PV (CPV) modules is that there is a specific design of lens over the cell that can either reflect the extra sunlight or focus it on the cell. Despite concentrating solar power, this technology uses the technology of solar thermal energy for producing electricity (Hootman, 2013). Figure 2.27 depicts some common collectors which are normally used to concentrate the light.

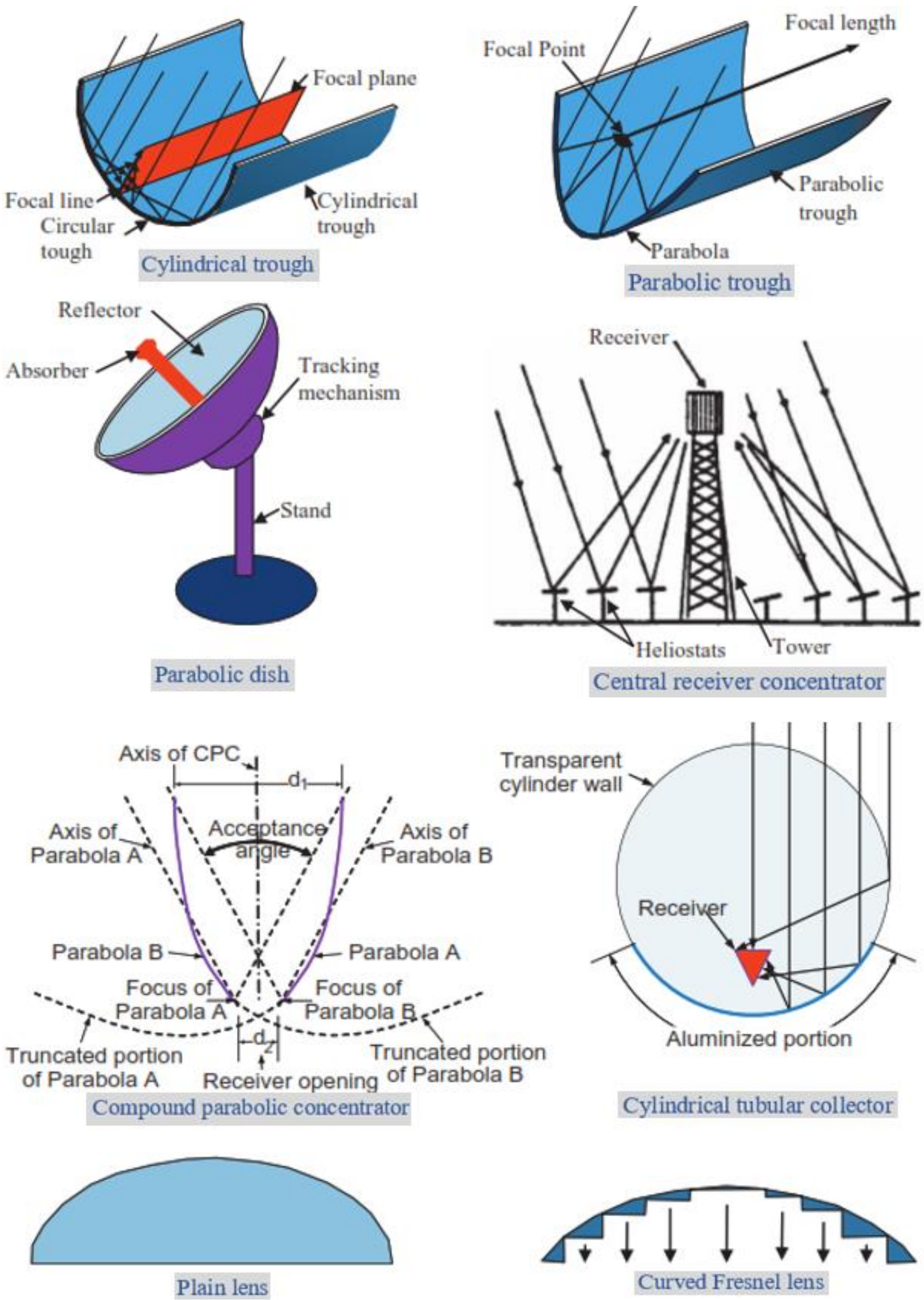


Figure 2.27: Different Types of CPV Systems (Agrawal, Tiwari, 2011)

2.1.7 Typology of the PV Systems

In general, three main categories are available for PV systems (see figure 2.28).

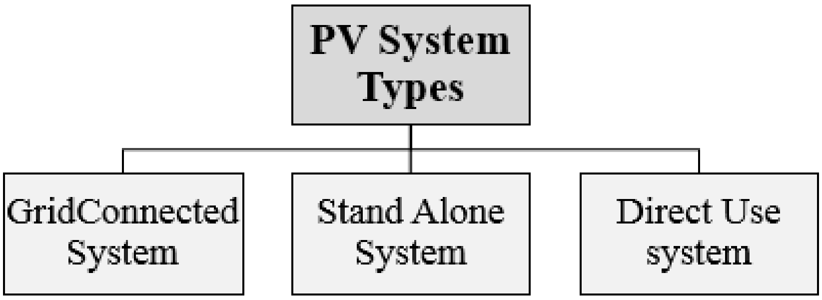


Figure 2.28: Typology of the PV Systems (Agrawal, Tiwari, 2011)

2.1.7.1 Grid-connected System

PV systems connected with grid exchange the energy generated with the national power grid. This system basically including the components as following:

- PV modules/array (multiple PV modules joined in series/parallel through the mounting frame)
- PV array combiner/junction box (with the protective device)
- direct current (DC) cabling
- DC main disconnect/isolator switch
- inverter
- AC cabling
- meter cupboard with the power distribution system, supply and feed meter, and electricity connection (DGS, 2008)

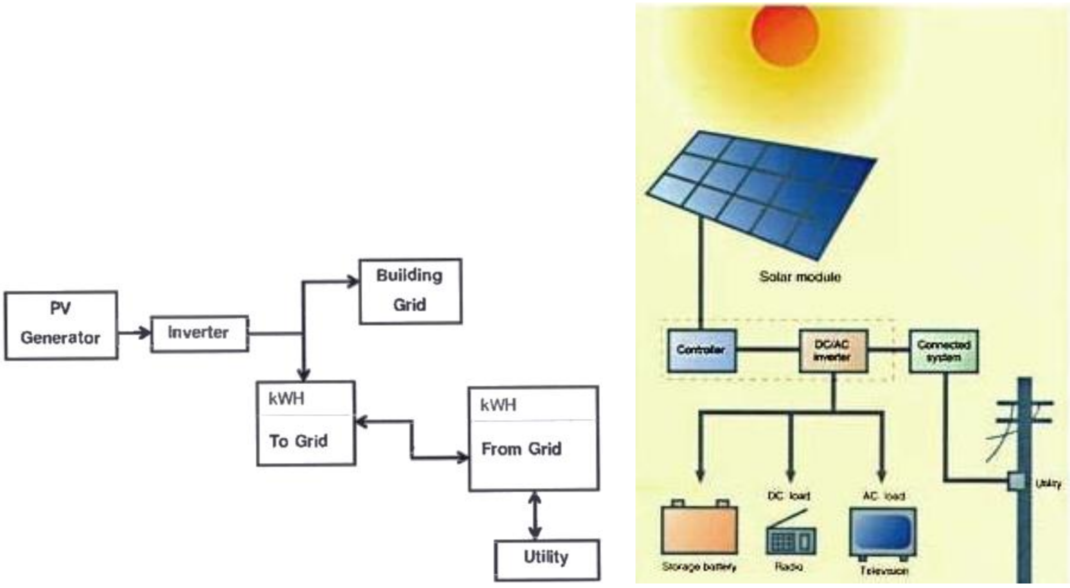


Figure 2.29: Schematic Diagram for Grid-Connected PV System (URL 14)

Exchanging power occurs in two directions: if the output of the PV generator is more than a given time period, the extra energy is stored in the national grid. When the energy amount not enough, the energy is provided by the grid. There are two kinds of energy meters to measure the energy exchange in two directions. For transforming DC current generated an alternating current of a photovoltaic system, an inverter is used, however. No batteries are required in the systems joined to the grid since the national solar electricity network is not available.

2.1.7.2 Stand-Alone PV System

Systems that are more effective in case of remote sites not connected to the electrical grid are called PV Stand Alone systems. This system should cover the whole energy demand and consists of the elements including:

- photovoltaic modules
- charge controller
- energy storage system (batteries)
- Inverter.

The battery is required in such systems whenever there is either no energy loads for charging the battery, or energy load is low. There is a charge controller that manages the process of charge and discharge, guaranteeing long-term battery life. Also, there is an inverter transforming DC to AC (Sick, 1996). Wherever power grid is not available or is hard to reach, these systems are more suitable economically.

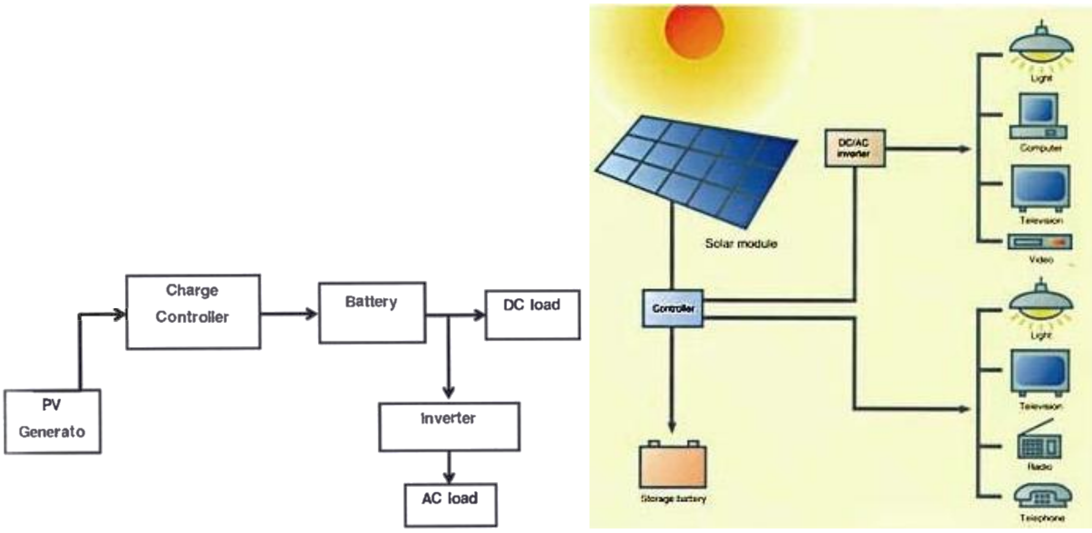


Figure 2.30: Schematic Diagram for Stand-Alone PV System (URL 14)

2.1.7.3 Direct Use System

The direct use system runs whenever the load is equal to the amount of radiation available, thus there is no need to store electricity or back up (Sick, 1996).

2.1.8 Optimized Factors for PV Output

Using photovoltaics is considered very effective as adaptive elements on the envelope of building such as a roof. However, the ability to be integrated into the building envelope is the actual capability of photovoltaic and thermal technology to generate energy. It should be guaranteed by the PV system designer that partial shade is cast on the modules. Otherwise, the output will be affected adversely. Standard forms of photovoltaic modules are available; however, they can be specially designed for any given project.

Nowadays, offering new materials, photovoltaic products have led to a steady improvement in the technology: it is a reliable product; its technology is modern, and its minimum expected service lifetime is 20 to 30 years.

A PV array's annual electrical output would be related to the following factors:

- Average of daily insolation annually
- PV array's tilt angle
- Azimuth, that is, orientation in terms of due South
- Shadowing (partial shading or overshadowing)
- Effect of temperature and ventilation
- Sizing

2.1.8.1 Annual Average Daily Insolation

The level of sunlight falling onto the surface of the earth differs due to various factors: Site location regarding latitude (how far it is from the equator) has the most important role. In general, as the distance between the equator and the array is more, the amount of irradiation will be less. As a result, the farther one goes northward, the amount of solar energy will be less, and the expected output of the installed PV system would be less. It does not mean that the systems in the North must be precluded for other factors must be considered as well (URL 15).

When it is known that mounting PV on a building is possible, the potential of electrical output performance is estimated. First of all, the electrical output is estimated through the level of solar energy captured at the site. An average of insolation received daily is a useful amount measured as kWh (this should not be mistaken with electrical energy, in which this unit is used).

The amount of daily insolation differs throughout the year, as it increases with day length as well as sun's altitude. For instance, Figure 2.31 shows daily insolation as the values of the monthly average of a site located in a northern latitude of Tabriz, Iran. Also, weather conditions and cloud pattern should be considered. Thus, the daily insolation can be calculated through all seasons and the value for annual average can be achieved.

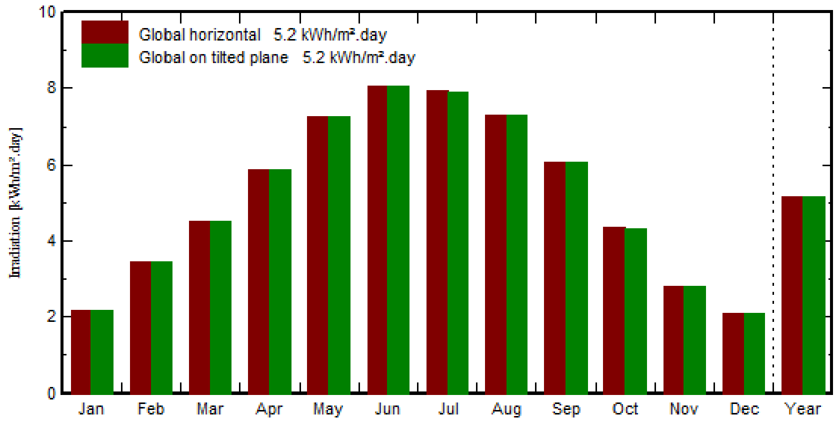


Figure 2.31: Monthly Averages of Daily Solar Radiation for Horizontal (0°) Surfaces in Tabriz, Iran (Author, 2021)

For the horizontal surfaces, the maximum monthly value of insolation for the location of Tabriz, Iran (Latitude of 38° North) in June is 8.06 kWh/(m2·day) and the minimum in December is 2.1kWh/(m2·day) while, the annual average is 5.16 kWh/(m2·day).

It is essential that PV panels no be located in places where adjacent structures or landscapes are present or might be constructed in future, as they can shadow the system. Electricity production can be inhibited if the panels are fully or partially shaded.

The system operates best whenever there is uniform solar access since a solar cell having the lowest level of illumination determines the operating current for the whole cells wired in that series.

2.1.8.2 Tilt Angle

The tilt angle is defined as the inclination angle between the horizontal plane and the PV plane which varies in the range of 0 to 90 degrees (figure 2.32).

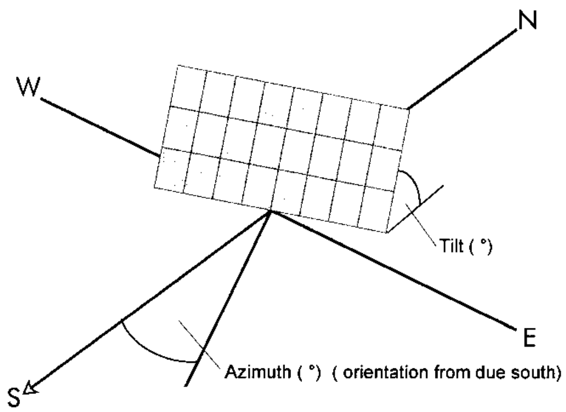


Figure 2.32: PV Tilt & Azimuth (URL 16)

The Highest Solar Intensity Takes Place on a Flat Surface which is Perpendicular to Solar Rays (Figure 2.33).

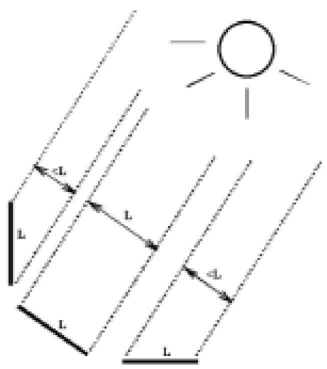
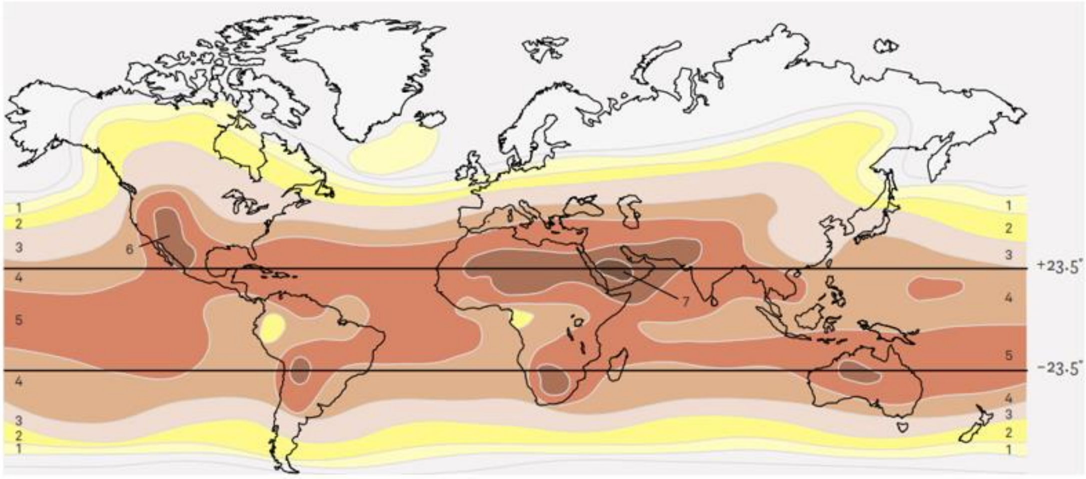


Figure 2.33: Received Various Solar Radiation Amount on Surfaces for Different Tilts (URL 16)

When the panels are inclined toward the sun, the level of sun rays that strike the surface increases, and this will result in an increase in the output. The path of the sun makes a daily arc that changes in each season. Likewise, the sun moves on a prescribed solar position, which is characterized by an azimuth angle (horizontal) as well as an altitude angle (vertical). Studies in this field have indicated that due to the relationship existing between tilt and output, installation tilt has a direct influence in the economics related to energy savings.

According to the thumb rule in the Northern hemisphere, PV installations generate the highest amount of energy throughout a year when they are oriented true South with a tilt angle equal to the site latitude. Of course, depending on the clouds and the position of the sun, the instant output will be different. The farther a panel is from a tilt equal to the site latitude, the lower total annual output will be.

When the tilt of the surface is about 20° less than the latitude angle, and where North of the Tropic of Cancer is oriented South, the insolation throughout the year will be in its maximum level. It should be mentioned that the map of values presented in figure 2.34 is for a horizontal surface, which is called the average daily global horizontal solar radiation. Some other maps provide the values for flat surfaces tilted South (in northern latitudes), at the angle equivalent to the latitude. This tilt causes an increase in the values for the sites located in higher latitude compared to the others depicted in the map. Figure 2.34 shows the optimal tilt and the corresponding output of solar energy for several geographic locations.



kWh/(m²·day)	kWh/(m²·y)	MJ/(m²·y)
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

Figure 2.34: Worldwide Annual Average of Daily Insolation on a Horizontal Plane (Tilt=0°) (Roberts & Guariento, 2009)

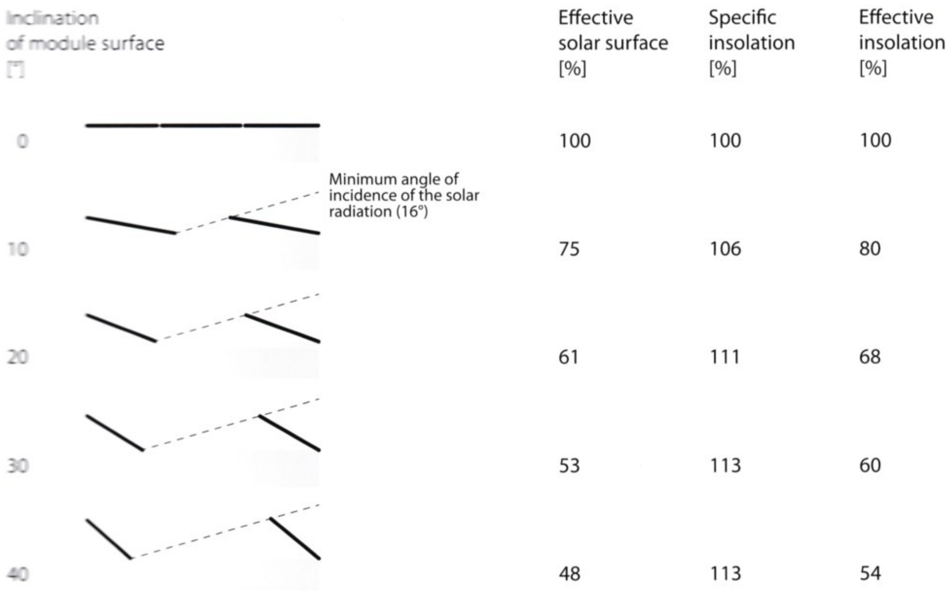
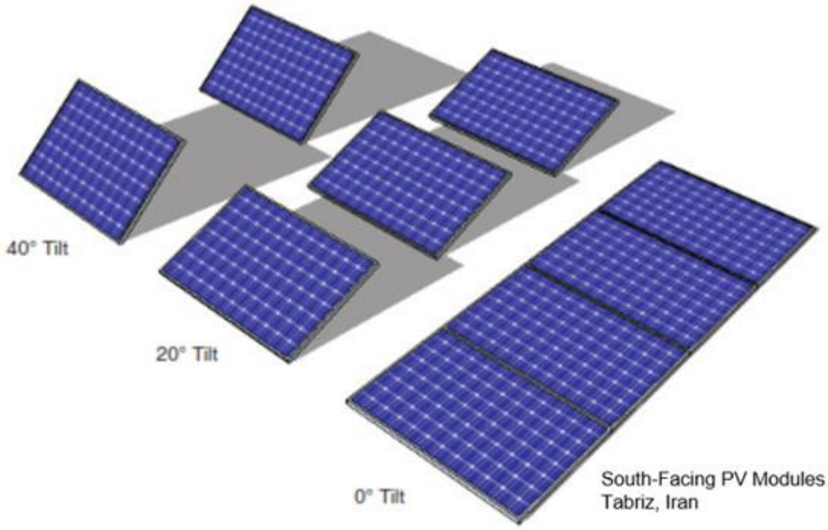


Figure 2.35: Roof PV System Arrangement Based on the Operative Surface area for Solar Insolation in Frankfurt, Germany (Hegger et al., 2016)



PV Module Tilt	Performance Factor (kWh/kW)	PV Module Peak Power (W)	Number of Modules	Annual Energy Generation (kWh)
0°	1098	220	4	966
20°	1200	220	3	792
40°	1205	220	2	530

Figure 2.36: Assessment the PV Tilt Effect to Provide Energy Based on the Spacing and Inclination of PV Module (Based on Data from NREL PVWatts Website, URL 17)

The theoretical framework analysis begins with a survey on the effects of various tilt angles through PV watt. PV watt, developed by NREL (National Renewable Energy Laboratory), is used to calculate photovoltaic system performance precisely. Such an analysis offers photovoltaic energy potential for a different tilt for the certain month of the year. In this analysis, 4 kW system having an output of 335 Watt with 12 photovoltaic panels was used. Here tilt is the photovoltaic array angle from a flat horizontal surface. Like the ideal tilt angle, the altitude and path of the sun vary in winter and summer.

Horizontal Azimuth is an angle that is usually measured clockwise from the North, which means that the angle facing South is 180 degrees. Once the azimuth angle fixed is 180 degrees, ideal for the area of Tabriz, and tilt is varied from 0, 10, 20, 30, 40, 50, 60, 70, 80 and 90 degrees, the kilo-watt-hour amount for producing renewable energy will vary. Each tilt affects renewable energy production for kilo-watt-hour/ year differently. In Tabriz region, the highest yield for renewable energy is obtained between 30 and 40-degree tilt (See Table 2.2, Figure2.38).

Table 2.2: Annual PV Output (kWh/yr) for Different PV Tilt Angles in Tabriz, Iran (Based on NREL's PVWatts Calculator, URL 17)

Tilt / Month	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°
1	181	210	233	251	264	270	270	264	253	235
2	258	291	317	336	347	350	346	333	313	286
3	352	375	390	397	396	386	369	344	312	274
4	373	383	386	382	370	351	326	295	260	220
5	464	467	462	449	427	398	362	320	274	225
6	590	588	576	554	520	476	424	364	299	236
7	557	558	550	531	502	463	416	361	301	240
8	470	481	483	475	458	432	397	355	306	252
9	412	440	458	466	463	450	428	395	354	304
10	329	370	402	425	438	440	432	415	387	349
11	230	275	313	342	363	374	377	371	355	331
12	172	204	232	254	269	278	281	277	267	251
Total (kWh/yr)	4388	4642	4802	4862	4817	4668	4428	4094	3681	3203

(Note: Latitude: 38.05° N, Longitude: 46.17° E; Array Azimuth of 180 Equals South Orientation)

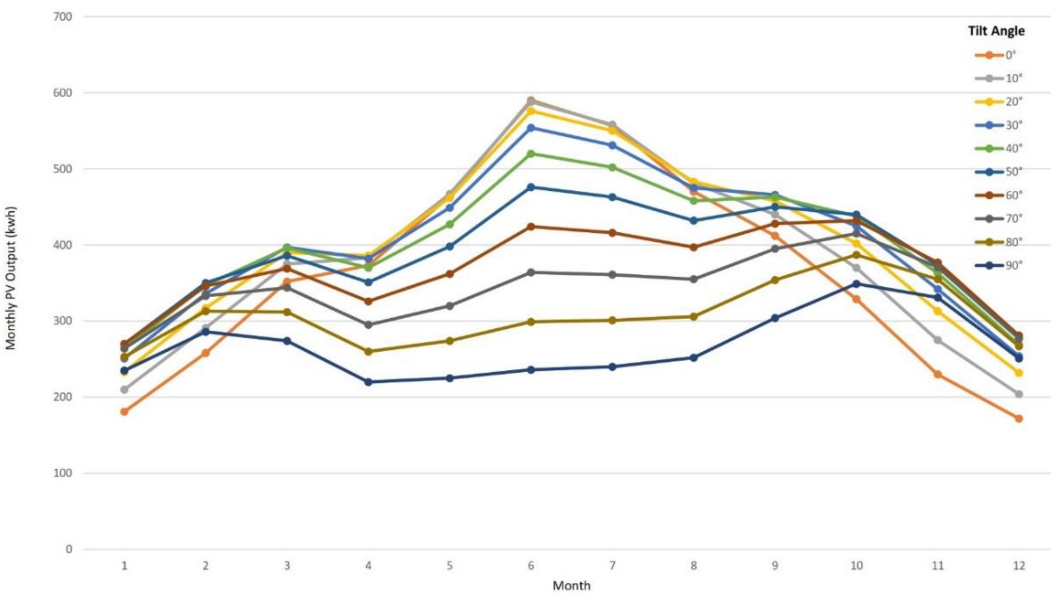


Figure 2.38: Monthly PV Output (kWh/m) for Different PV Tilt Angles in Tabriz, Iran (Based on NREL's PVWatts Calculator)

Tilt angle for a photovoltaic panel is considered as a key factor for optimizing the yield of renewable energy coming from the sun. So, identifying the best tilt possible for photovoltaic arrays of the project and determine the design for optimizing is so important.

2.1.8.3 Orientation

The overall level of energy striking a surface is a function of orientation and tilt. The surface orientation selected for PV integration is an important criterion in planning. However, module orientation must be considered (URL 18). On the facades facing East and West, the efficiency of PV systems is less compared to those oriented South. However, in PVs that are mounted vertically and have an orientation of East/West, the yield is 60% of southern orientation with optimal inclination. In the orientations of East/West, the most power is generated at the early as well as the last hours of the day when the sun's angle is low. The following figure indicates the impacts of different array inclination and orientation on the system performance. Figure 2.38 is an example of a place located in the UK and shows maximum yield percentage, which might be expected for various orientations and angles.

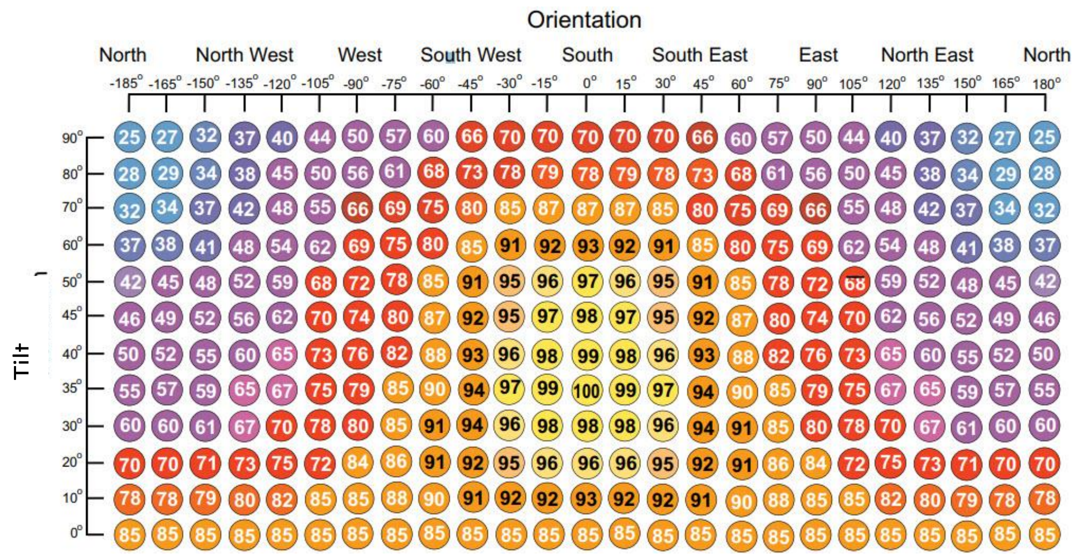


Figure 2.38: The Efficacy of Tilt and Orientation in the Central Parts of UK (URL 19)

In the modules having South orientation which are inclined around 35° from the horizontal surface, the highest solar yield is allowed (in central Europe) on an annual average basis. However, South-East to South-West deviations is accompanied by minor yield losses. Furthermore, a vertical installation facing South gains around 3/4 of radiation as opposed to identical orientation (URL 20). Figure 2.39 helps measure insolation increase and a decrease in accordance with orientation.

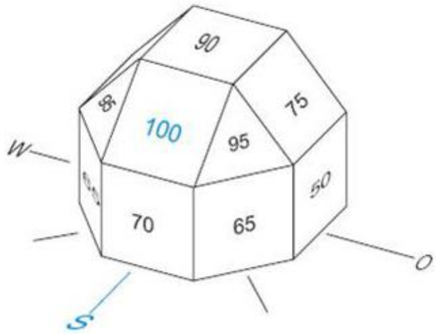


Figure 2.39: Impact of Orientation on Insolation Annually for Central Europe. 100% Energy Yield at Around 35° Southern Inclination (Hegger, 2008)

It must be taken into account that solar radiation intensity on different envelope surfaces is not the same. Therefore, its value on North façade is very low (existing in the early morning and late afternoon) and might not be considered. In fact, there are only three effective vertical surfaces except North (depending on orientation) plus horizontal surface of the roof which has the highest importance among them (See figure 2.40).

Ir: solar radiation intensity $\boldsymbol{Ir}_{(Roof)} > \boldsymbol{Ir}_{(South)} > \boldsymbol{Ir}_{(West/East)} >> \boldsymbol{Ir}_{(North)}$

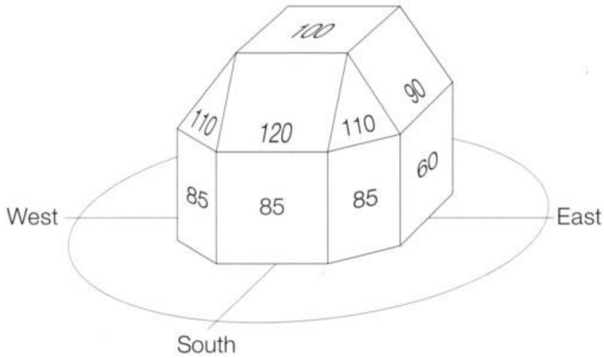


Figure 2.40: Orientation Impression on the PV Yield in Germany (Hegger, 2008)

Energy yields from active solar technologies integrated into the building depend on the orientation and inclination of the building surface. Irregular guidance values can be of great help once the project starts. However, in other detailed designs, these initial estimates should be checked using calculations according to actual systems. These indicate that insolation on a wall facing South is 15% less than the insolation on a flat roof. Among other important factor is the seasonal distribution: the angle at which sun's rays strike the façade integrated panel results in generating more energy each day in winter and transition months compared to a system on a flat roof. Therefore, active surfaces on the façade are able to satisfy the building's requirements, depending on what the purpose of generating energy is (maximum yield throughout a year versus yield evenness or relevance of winter). So, solar energy yield ratio in the central Europe would be:

$Ir_{(Roof)=}1.00$, $Ir_{(South)=}0.85$, $Ir_{(West/East)=}0.6$

Where, Ir is irradiation and Ir_{Roof} is set as a reference (1.00)

Efficiency in relation to tilt as well as an orientation at 35° latitude shows that 90% of maximum generation is provided by most combinations of tilt and orientation, which demonstrates that PV placement has significant flexibility. As PV is used in a range of configurations, it is seen as a commonly used building material (see table 2.3).

2.1.8.4 PV and Shadowing

Many factors affect PV systems' efficiency, shadowing being the most important. The design of a PV system must be in a way that no shadows fall on during the day. The detailed figure is provided by simulation programs.

Table 2.3: Optimum Tilt for Different Locations Based on Solar Intensity Output (Based on Data from NREL PVWatts Website, URL 17)

Location	Orientation (Longitude, Latitude)	Optimum Tilt Angle °	Energy Output kWh/m2/y
Berlin	13, 52	35	121
London	0, 52	35	111
Madrid	4, 40	35	201
Lisbon	9, 39	30	201
Rome	13, 42	35	191
Amsterdam	5, 62	40	129
Geneva	6, 46	30	143
Krakow	20, 50	35	124
Oslo	11, 60	45	130
Athens	23, 38	30	183
Budapest	19, 47	35	143
Vienna	16, 48	35	132
Istanbul	29, 41	30	176
Abu Dhabi	55, 25	25	223
Perth	116, –32	30	227
Melbourne	145, –38	30	182

Location	Orientation (Longitude, Latitude)	Optimum Tilt Angle °	Energy Output kWh/m2/y
Brisbane	153, –28	25	189
Mexico City	–99, 19	20	205
Miami	–30, 26	25	220
Los Angeles	–117, 33	30	233
New York	–74, 41	35	169
Seattle	–122, 47	35	147
Tucson	–111, 32	30	253
Buenos Aires	–58, –34	30	201
Cape Town	18, –35	30	232
Nairobi	36, –1	5	203
Bangalore	77, 13	15	217
Delhi	77, 28	30	233
Tokyo	140, 35	30	149
Singapore	104, 1	0	171
Hong Kong	114, 22	20	156
Moscow	56, 37	40	119

2.1.8.4.1 Shading Effect on Crystalline Modules

The overall electricity of the module is determined by the weakest cell in the solar cell string. For instance, shading (partially) can weaken the cell. If so, electricity decrease cannot be linear, but inconsistent with the shaded area of the module.

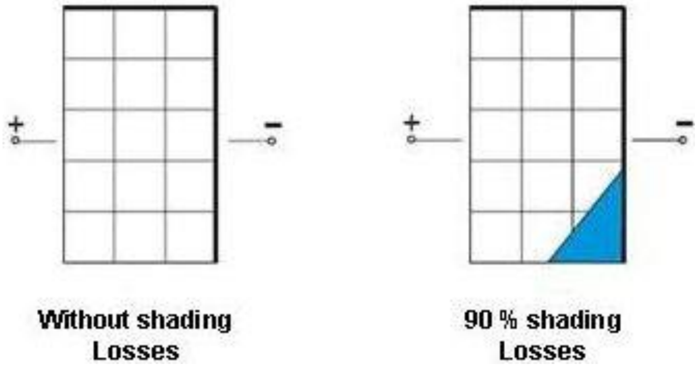


Figure 2.41: Partial Shading Effect on Crystalline Module Performance (URL 21)

2.1.8.4.2 Shading Effect on Thin-film Modules

Partial shading leads to a slightly smaller decrease in output in modules of thin-film. As the design of the cells in the module of thin-film is strip-like, the whole cell cannot be entirely shaded. Therefore, the output decrease is usually only equal to the shaded area. The spacing of module which is based on the angle of shading reduces shadow's cast in other modules placed in rows (see figure 2.42).

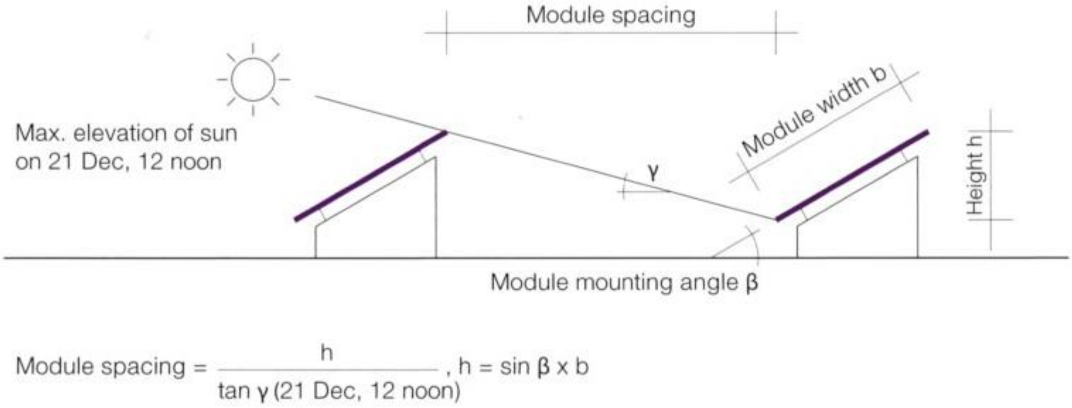


Figure 2.42: Module Pacing Calculation for PV Modules' Rows on a Flat Roof (Hegger, 2008)

2.1.8.4.3 Principles for Shadowing Minimization

Having a site with the least shading is desirable. Shadowing depends on the site's geography, surrounding structures and self-shading forms of buildings. It is possible to lessen the effects of shadowing via system design (URL 21). In an architecture design, it is implied that obstacles such as telephone poles, trees, chimneys, other structures or even some parts of the array itself have to prevented wherever possible. Moreover, the relevant areas for using PV will be achieved based on the sun's altitude if the shading elements of the building's southern view are changed to opposite façades (West, East, and North).

If the block is planned on a city scale, taller buildings must be located on the northern side stepping down in a progressive manner to lower buildings southward. In addition, module spacing performed according to shading angle reduces shading cast by other series of modules placed in a row. Shadowing has to be prevented if possible. If it is unavoidable, selecting configuration and components of the array carefully can result in minimum losses.

Self-shading arising from the architectural form must be kept away. Some strategies are considered to avoid the shading effect on PV output:

- Rooftop features such as chimneys, stacks, lift rooms, water tanks, and ventilation stacks, etc. have self-shading effect with considerable impacts on the PV output, thereafter, positioning the obstacles on the North is mandatory.
- Façade obstructions like staircases might be located to the North or in a position without shading effect on PVs.
- Separation of the facades from trees beside utilization of deciduous trees which lose their leaves in winter would be beneficial regarding long-period shading effect on PV’s.

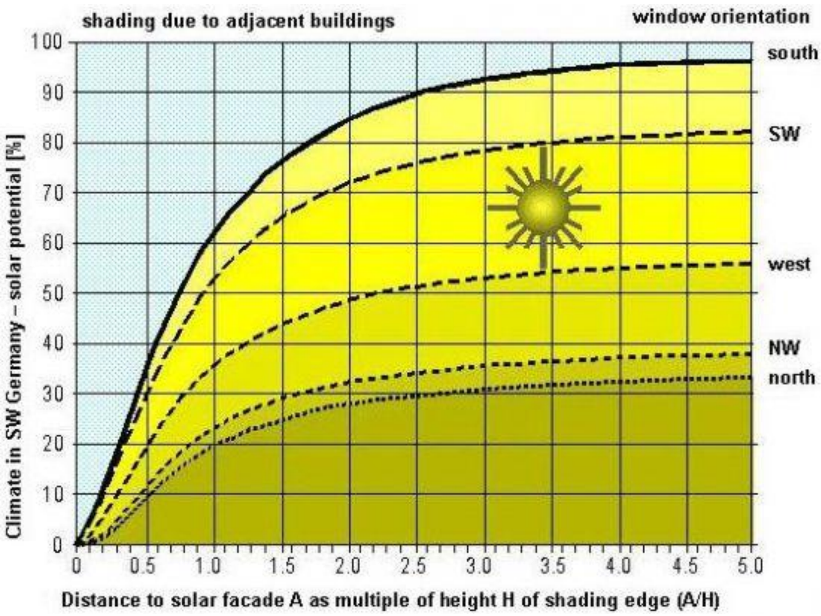
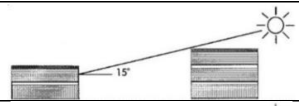
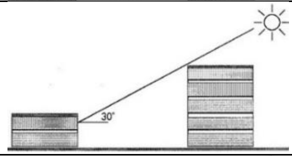
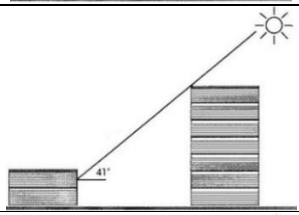
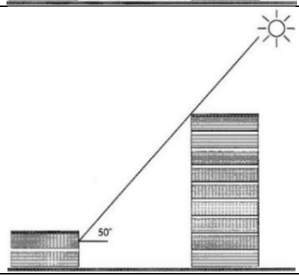


Figure 2.43: Shading Impacts of Adjacent Buildings in South-West of Germany (URL 22)

Table 2.4: The Effect of Shading due to the Neighbored Buildings in London, UK (Reference Building Height is: h) (Adopted from Thomas et al.,2001)

Adjacent Building Height (h)	**Shading Angle**	**Unshaded PV output**	**Schematic drawing**
1.5 h	15°	83%	
2.5 h	30°	61%	
3.5 h	41°	46%	
4.5 h	50°	36%	

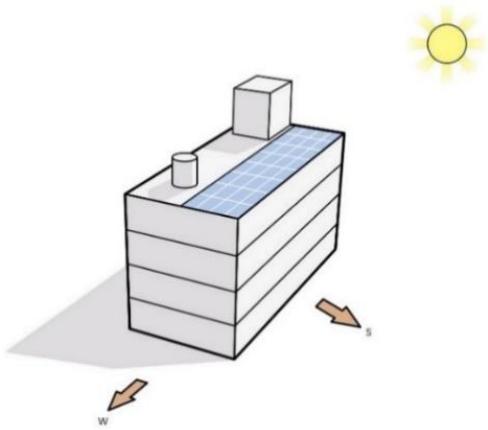


Figure 2.44: Roof Features Should be Kept Away of Overshadowing on PV Arrays (Roberts & Guariento, 2009)

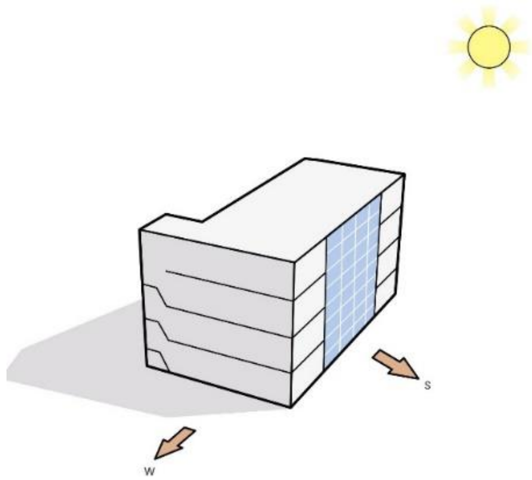
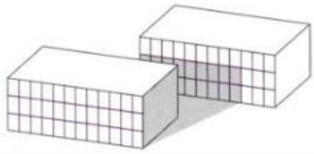
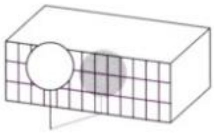
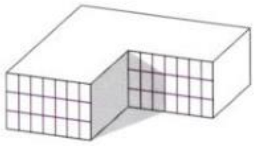
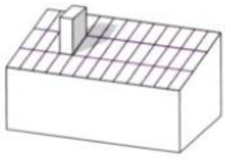
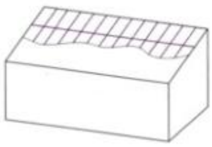
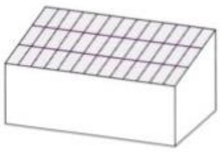


Figure 2.45: Placing the Staircase on North and Keeping the South Side Clear to Avoid Overshadowing on the Vertical PV Arrays (Roberts & Guariento, 2009)

Table 2.5: Possible Shadowing Causes and Related Solutions (Adopted from Weller et al., 2010)

Possible Shadowing Causes	**Schematic Drawing** ↗ **N**	**Possible Solutions**
Adjacent buildings		-Using appropriate free-shading distance between buildings
Plantation		- Leaving the South side clear - Separating trees from PV façades - Using deciduous trees which loose leaves in winter - Planting trees on the North side of buildings (northern hemisphere) - Only planting small trees with limited growth up to roof height - Yearly pruning of trees to avoid shading of the PV collection surfaces
Building projections		-Avoiding the overshadowing on the vertical PV arrays - Modification of the building geometry - Architectural form correction
Rooftop structures		-Avoiding overshadowing of roof features on PV arrays - Putting the roof obstacles on the North
Snow & Soiling	 	- Using self-clean modules with an angle over 20° - To keep clean the modules by special treatment with PV Guard - Roof cleaning (manually or automatic by PV-robots)

2.1.8.4.4 The Effect of Temperature and Ventilation

Despite the solar water heater function which works better with higher temperature, the PV performance is different because by increasing the temperature, the module efficiency decreases. A temperature increase in a module causes a performance decrease (for example 0.5% per 1°C higher than STC for a crystalline module) (Thomas et al., 2001).

Depending on the production process in amorphous silicon cells, the effect is almost half of the value mentioned above. PV output is reduced by the dirt effect. However, applying a tilt angle of 5º would be adequate for PV self-cleaning on rainy days. (URL 19)

Under steady circumstances, the output of PV has the direct relationship with the area PV is installed in square meters (A_{PV}), the PV module efficiency ($ή_{PV}$), as well as the plane of the array of irradiance (GT), while having an inverse relationship with temperature of a module. (T_{PV}) (See the following equation). However, a reverse ratio exists between PV power output and temperature. In other words, increasing the PV module temperature would lead to its decreased effectiveness.

$$PVoutput \quad \alpha \quad T_{PV} \,.\, ή_{PV} \,.\, GT \,.\, A_{PV} \qquad (1)$$

The heat loss capability of PV module is important for heat dissipation. So, where possible the air gap employment to the PV array rear which is minimum 25 mm, accelerates sufficient ventilation for decreasing the PV temperature behind (see figure 2.46).

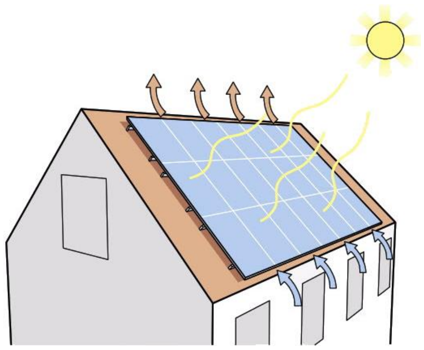


Figure 2.46: Scattering (Transporting Away) the Solar Heat Gain from PV Modules by Rear Ventilation (Roberts & Guariento, 2009)

A ventilation layer with an approx. 10cm on façades and roofs is needed for increasing the electricity yield. It must be noted that, although ventilation- an advantage- has an impact on the PV electricity yield, it is not essential. Once electricity yield is compared in PV modules having ventilation and the ones lacking ventilation, it is observed that the yield in the PV modules lacking ventilation is about 10% less (URL 23). Furthermore, a decrease in the output of thin-film modules at high temperatures is less than that of crystalline. Owing to the lower temperature coefficient, a decrease in the output in the summer, i.e., when the module temperature is high, is about 10% less than that of crystalline modules (Bächler). Nevertheless, thin-film modules require more area since their efficiency is lower compared to poly- or monocrystalline modules in order to have the same level of output.

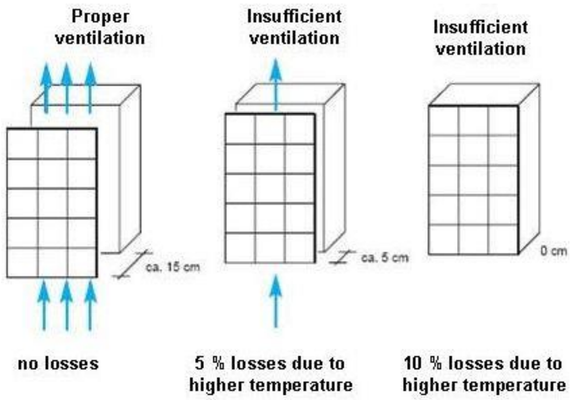


Figure 2.47: Inverse Ratio of the PV Yield and Module Temperature Regarding Ventilation (URL 23)

2.2 Building Integrated Photovoltaics (BIPV) and Architectural Relationship

In a building's architectural design, the emphasis is not only on meeting the requirements related to cost-effective, rational, and functional issues. The architecture consciously deals with the ways in which perceptive senses are involved with the view, aiming at establishing an experience with the shape as well as the whole structure of space.

The description of the features associated with architectural design and planning represents how important it is to consider design concept with respect to installing PV modules on buildings. That is how a PV module can function as an indispensable element of the entire experience of design and space (Hagemann, 1996).

PV systems mounted on buildings are divided into two major groups of building-integrated PVs (BIPVs) and building-attached PVs (BAPVs) (Barkaszi and Dunlop, 2001). If the approach of installing PV on the building is not mentioned clearly, identifying a PV system as building-integrated (BI) or building-attached (BA) may be difficult (Jelle et al., 2012), (Hagemann, 2002).

2.2.1 Building Applied Photovoltaics (BAPV)

BAPVs do not have any direct impact on the function of the structure once they are mounted on a building (Barkaszi and Dunlop, 2001). Peng et al. (2011) indicated that when the integration is possible by mounting a PV module over the structures (retrofitting), the system is referred to as building applied photovoltaic (BAPV).

Zomer et al. (2013) assessed BAPV performance for different building types. Consequently, they offered to apply the optimum orientation and inclination angles for PV panels for maximum annual yield.

2.2.2 Building Integrated Photovoltaics (BIPV)

Building Integrated Photovoltaics (BIPV) is determined as PV module application for integration in the envelope of the building (conventionally into roof/facade) (URL 26) by substituting typical building materials (Henemann, 2008) and acting as an inseparable segment of the building element to make the dual function of adjusting the interior environment and energy generation as well (Jelle et al., 2012).

The global growth of BIPV system is high and its value has a direct influence on the decision-making procedure. Furthermore, as this technology is multifunctional, it is generally designed to have more than one role for integration into the building as whole. (Attoye et al., 2017).

In contrast the BAPV, in BIPV -which performs as on-site building exposure- the modules incorporated into the available architecture of different building types. Moreover, the needed off-site (open space) to install the PV panels and loss rate for electricity distribution are reduced.

As it is illustrated in figure 2.48, many parameters have to be taken into account while integrating PVs into building envelope (Bloem et al., 2012). Architectural and aesthetical features are not included BIPV definition. Integration into the building must include both technical and aesthetical aspects. Technically, through integration, some of the components and materials of a building are replaced. Aesthetically, through integration, solar system as an element of the entire design, gives value to the design.

Besides, a building with a good design, and PV system with a desirable integration will affect everyone positively (Reijenga & Kaan, 2010).

Figure 2.48: PV Integration Parameters in Building (Bloem et al., 2012)

2.2.3 The Development of BIPV as Photovoltaic Type

In 1970, the application of solar PV modules for integration in buildings started through the advanced sponsored project with the help of U.S. Department of energy (DOE). PV modules having aluminum frame were generally installed on, or connected to buildings' skin in remote regions where there is no access to electric power grid. (Akash & Baredar, 2016). Constructed in 1979, the Carlisle House is known as the first BIPV having "Net-Zero" energy house. This amount of energy this building generates is as much as it consumes throughout a year.

Since then, the priority has been given to the characteristics of BIPV and its function. Adding PV module to the roofs emerged in the 1980s. Such PV systems were commonly mounted on the buildings connected to utility grid in the regions having centralized power generation (Ted et al., 2011).

The emergence of BIPV occurred in the 1990s when a radically new idea was born out of solar cells, which has been regarded as an appealing technological product which was particularly designed to be connected to the building envelope, and it became commercially accessible (Eifert, 1998).

In 2011, An economic report regarding BIPV history suggested the possible ways to overcome the technical challenges before the competitive cost of BIPV installation with PV modules (Kylili & Paris, 2014).

Notwithstanding, nowadays considering to the public awareness, BIPV system will turn to the inseparable part of the European Zero Energy Building (ZEB) goal for 2030 (Temby et al., 2014).

Only a few researchers have carried out performance-based studies in BIPV systems, which mainly rely on simulations. The simulation models available still need to be developed completely. And in order to be applicable, they need to be validated carefully. (Carr, 2005). This is because PV performance is influenced by many complex interwoven factors (Aaditya and Mani, 2012), which needs to be incorporated as a complicated study model.

2.2.4 BIPV Performance

Various factors must be considered for optimum function of BIPV cells (Salema & Kinabb, 2015). Temperature of the cells is one of the main parameters that has effect on BIPV cells (Garcia & Balenzategui, 2004), and it depends on the thermal features of the materials constituting PV cells, the installation and encapsulation mode, their type, and weather conditions as well (King et al., 2004).

In order to avoid a weak performance caused by temperature excess, the functional temperature of the cells must be controlled (Trinuruk et al., 2009). One method suggested to avoid this excess temperature which is due to unabsorbed irradiance is the use of ventilation through natural or forced convection alongside PV panels. After studying several models, panel temperature is expected to be at an accuracy of 50% (Vareilles et al., 2006). However, the performance of PV cells is largely affected by their orientation, which influences solar radiation incident, and hence electrical power output. In an attempt to increase the system efficiency, Yang & Lu (2007) devised a mathematical model to improve the azimuth and tilt angles as a function of weather conditions in Hong Kong.

In order to mount PV panels in BIPV project, the previously mentioned parameters need to be studied and optimized. Performing this project in a given rural or urban area necessitates a sensitivity analysis as well as its validation. Therefore, Cheng et al. (2009) carried a study concerning the factors influencing panel performance through a program called PVsyst in 20 sites, all of which are in the northern hemisphere. There was almost no difference between the values of the simulator and the data deriving from three different databases. In order to find the best tilt angle, the simulations of 20 different locations were repeated every 10 degrees. The variables employed in simulation were as follows: a one-square-meter area, a standard module of 180 Watts, the façade as mounting position, southern orientation, monocrystalline technology, and ventilation character. The best tilt angle obtained was identical with latitude angle for each location in the study. It was also pointed out that the simulator was capable of obtaining around 98.61% of PV performance in all 20 locations.

2.2.5 BIPV Barriers

Nowadays, BIPV is discussed by architects, engineers, contractors, and building owners as an ingenious technique for eco-friendly energy generation and reducing environmental pollution (Salema & Kinabb, 2015). The PV cell importance as the main matter for various amplifications in the later decade has been lasted until now; albeit, BIPV utilization in buildings is harnessed yet because of lots of barriers including:

- Aesthetical: When PV modules mounted on the existing structure are not an integral part of buildings, a strange component is formed in the architecture. Building stakeholders consider the system's perception in a building as the main element of reserve.
- Technical: In normal conditions, a large space is required for the installation of PV modules, something that cannot be always possible on the roof of a building. Moreover, roofs are inappropriate sometimes, and achieving the best orientation can be difficult as well.
- Social: As people are unfamiliar with this technology in the Mediterranean region (especially southern and Eastern part of the Mediterranean basin), they are not ready to admit this energy source is reliable. Many campaigns and training courses are being held in the regions towards BIPV design.

If BIPV is mounted on the building as an integrated element just like other regular elements of buildings, aesthetical problems can be prevented. The BIPV area required can be expanded and cover most part of the envelope, generating the desired amount of energy. When BIPV system is a component of the envelope and used instead of other conventional components, it will not impose additional costs to the existing structure. In addition, not only do these components offer other function like cladding, shading and insulation, they will also act as energy converters. although various integration types are available, here they are divided in two groups: façade and roof integration. Façade integration must be prioritized especially because of its accessible area exposed to the radiations, which generally covers the roof and is even larger. And when collectors are installed vertically in mid-latitudes, overheating risks are prevented in summer; therefore, performance of the system improves. This is understood well through a better distribution of radiation throughout a year compared to the radiation on collectors. the implementation of BIPV varies considerably from country to country because of many parameters: built environment, governmental and regional policies, electricity infrastructure, consumer demand, climatic conditions, and tariffs for BIPV systems connected to grid. According to Prieto et al., (2017), there are several obstacles regarded as restrictions for extensive adoption of BIPVs, which range from general issues concerning products like technical complexity, performance and aesthetics to more specified issues of the region like educational requirements on public and professional levels. Yang (2016) believes such problems can be solved by means of research, developing and customizing BIPV designs having good architectural integrality and aesthetics.

2.2.6 The Adaptability of BIPV in Building Design

A BIPV system will be successful if there is an interaction between PV system and building design (Prasad & Snow, 2005). By integrating PV system in buildings, conventional building materials like tiles on the roof or cladding on façade are displaced (Table 2.6).

Table 2.6: BIPV approaches Based on Increased Value of Architecture (Prasad & Snow, 2005)

PV is applied invisibly
PV is added to the design
The PV system adds to the architectural image
The PV system determines the architectural image
The PV system leads to new architectural concepts

Another approach, which is equally valid, is the use of PV systems but not as intrinsic element of the building's façade, rather placing it onto building's element, i.e., a roof, etc. PV systems integrated in the architecture is categorized into the following five approaches as following:

2.2.6.1 Applied Invisibly

Since PV system is mounted seamlessly, it does not harm the architecture. As an example, the PV covers the roof and is hardly visible in Maryland, the USA. Because the building is of historical significance, such a solution is selected. Here, modern materials with high technology cannot be suitable for such architectural style (Sick, 1996).

Figure 2.49: PV on the Residential Building, Maryland, USA (Prasad & Snow, 2005)

2.2.6.2 Added to the Design

A design function may be missing in the building, something that a PV can fit like a PV shading device as illustrated in a building in Madrid (Figure 2.50). This happens when the aim of internal spaces in buildings changes, or when the comfort levels must improve. In such conditions, mounting PV onto a building does not result in an ungraceful outcome (Gyoh, 2000).

Figure 2.50: IES Building, Madrid, Spain (Gyoh, 2000)

2.2.6.3 Added to the Architectural Image

When a PV system is integrated into the entire design, it complements the architectural image without being dominant in the projects. This means the best type of integration is contextual. A visual effect is provided by PVs, which, in turn, provides either minor or significant changes to the building's architectural dynamics. The PV Facade and roof canopy of the EMPA building gives a visual effect to designing without dominating the original shape of the building (Figure 2.51).

Figure 2.51: EMPA Building, Switzerland (Prasad and Snow, 2005)

2.2.6.4 Architectural Image Definition

A PV system acts as an integral component of the building envelope, and as a result, offers harmonic features to the building. Figure 4 shows buildings in Langedijk, in which PV is used to dominate aesthetic texture in the region and the roof feature as well. Though it may sound unconventional, the blue PV roof blends the sky view and the water effectively (Abro, 1999).

Figure 2.52: 5 MW PV Generation by Sttlement of Langedijk, Netherlands (Abro, 1999)

2.2.6.5 Exploration of Novel Architectural Concepts

PV modules used along with passive solar design result in new architecture and designs. Figure 2.53 depicts translucent features of PV, which can be dynamic or curved surfaces acting as an essential component of the building. Architecturally, this represents new options of designing, in which different support materials and supplemental building materials are used, e.g., steel and wood. Above all, the architect is able to experiment and control with the dynamic of natural lighting, transforming not only the color but also the feel of internal spaces as the position of the sun changes throughout daylight hour. This leads to new innovative and interesting architectural forms in buildings (Abro, 1999).

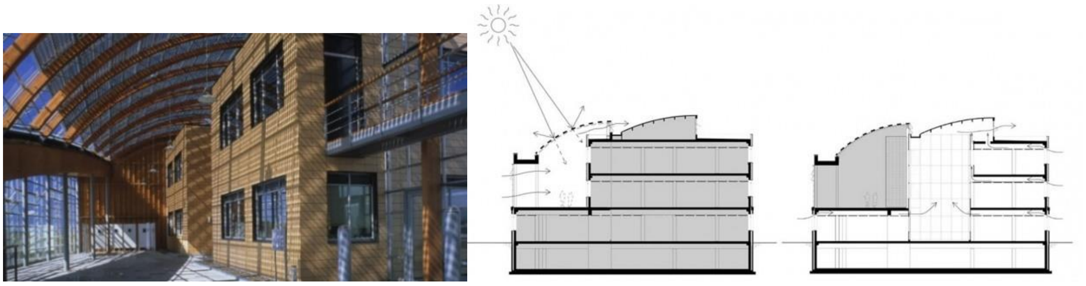


Figure 2.53: Application of Transparent PV Modules in Conservatory Interior, ECN, Netherlands (URL 24)

2.2.7 Architectural Criteria Regarding Proper BIPV Design

The main concern of an architect is not only whether to integrate PV into the design, and what physical, financial, mechanical, organizational and electro-technical conditions of a building will be; but also, how to integrate PV with regard to aesthetic features. As there are numerous architecturally inadequate solutions, it is obvious that lots of architects have not been able to handle this problem.

According to the results of the PV program of International Energy Agency (IEA PVPS) within a specific task referred to as Photovoltaics in the Built Environment (Task 7) with an architectural background, the aesthetic standards as the key requirements need to be observed (criteria for designing PV projects having good quality), which are the designer and architectural critic's guidelines leading to produce successful integration of PV are as follows: The integration suitability is affected by the materials, the design, surface finishes, size, dimensions and subdivision of the components. These, mentioned above, must always consider the constructional system as one unit. In order to have successful integration, it is serious to discuss the PV integration from the early stage of the design process:

- In order to guarantee the best integration into the façade or roof, the initial step in the designing process concerns taking into account how many modules will be used, and what the system's dimensions and the whole dimension will be.

- Even very small objects must be considered as they can cause shading problems for PV panels.

- Regarding integrating PV modules in buildings and also improving their performance, they must be designed to function at lower temperatures. In addition, using the heat obtained by the heat transfer fluid used to heat the air or function as hot water must be possible.

In real buildings, there are angles and forms that have to react to more than output of the PV array, which must be recognized in the design development.

2.2.7.1 Normally Integrated PV System

The building structure is naturally formed by the PV system within the added finishing touch (Figure 2.54) viz. with the PV absence, it seems the building missed something- whereas PV system fulfills the building. In this case, it would receive visually acceptable. Also, it is not necessary for the PV system to be that recognizable. When the building is renovated, the outcome must look as if the PV system had already existed there.

Figure 2.54: Fitted Transparent Panels into the Bent Roof of the Fire Station, Houten, Netherlands (URL 25)

2.2.7.2 Architecturally Satisfactory of PV System within the Building Context

The design needs to be architecturally satisfactory. The building itself must look attractive and the PV system must not improve the design considerably. This issue is really subjective; however, some buildings are, undoubtedly, more satisfactory than others. Also, thanks to special lighting, the PV system leads to attractive interior. Besides, mounting vertical blinds as an integrated system makes the building visually attractive.

2.2.7.3 Well-Composed Colors and Materials

PV systems must have the texture and color which are compatible with other materials of the construction. There would be an appropriate composition and configuration between colors and materials. A particular design is usually taken into account in the PV system (e.g., framed vs. frameless modules)

2.2.7.4 Well-Harmonized and–Composition

A PV system's dimensions should be consistent with the building's dimensions. Also, the PV system's sizing and the sizing as well as the building's grid are consistent (a grid of ¼ modular system of lines and dimensions for the use in building structures). In figure 2.70, while renovating the building, a façade which is more open was added.

A glazed sun protection as well as PV cells are protected by a great deal of glass. This system completely fits the dimensions and shape of the windows it covers.

2.2.7.5 Well-Contextualized PV System

The entire appearance of the whole building has to be compatible with the PV system might be employed. Using tiles or slates on historic monuments will make them look better compared to large glass modules. However, a PV system with high technology will most likely look better on buildings with high technology. The whole image a building represents should be consistent with the PV system. The whole building image should be in harmony with the PV system.

2.2.7.6 Well-Engineered Systems and Integration

This is not related to the water-proofing of the PV roof, but concerns more to the elegance of the details with pay attention to the detail's well-conceiving, minimizing the materials' mount to ensure the whole system performance is acceptable.

2.2.7.7 Innovative PV-Integrated Design

Innovative design for PV integration requires creative thoughts and bright ideas of architects albeit different ways has been examined. This method can promote the added-value to the buildings and increase the PV market.

Table 2.7: General Criteria for Good PV Incorporation in Architecture (Author, 2019)

Natural integration of the PV system
The PV system is architecturally pleasing, within the context of the building
Good composition of colors and materials
The PV system fits the grid, is in harmony with the building and, together, forms a good composition
The PV system matches the context of the building (contextuality)
The system, and its integration, are well engineered
The application of PV has led to an innovative design

2.2.8 BIPV Opportunities in Building Envelopes

The building envelope (roof and facades) is considered as a building's 'system layer'. Along with the structure, space plan and services, the ‘skin’ is one of the essential layers of any building. According to the statement by Stewart Brand, a building might destroy itself as a result of various levels of change in its components.

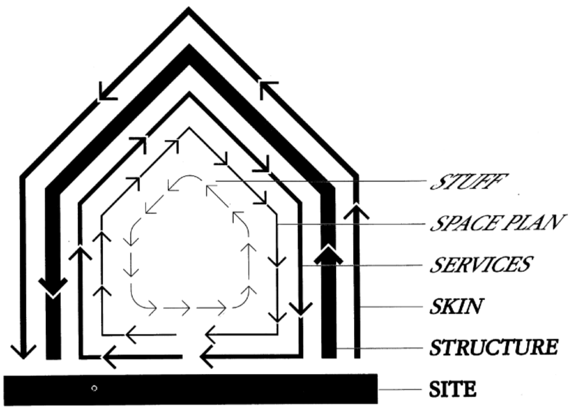


Figure 2.55: Different Layers of the System Based on Stewart Brand Different Layers of Change (URL 27)

In 1981, the concept of "a wall for all seasons" was described by Mike Davies and Richard Rogers. Unlike conventional facades, rather than being passive, the future facades will react actively to conditions in and out of the building. Active façade concept is being accepted in the 21st century.

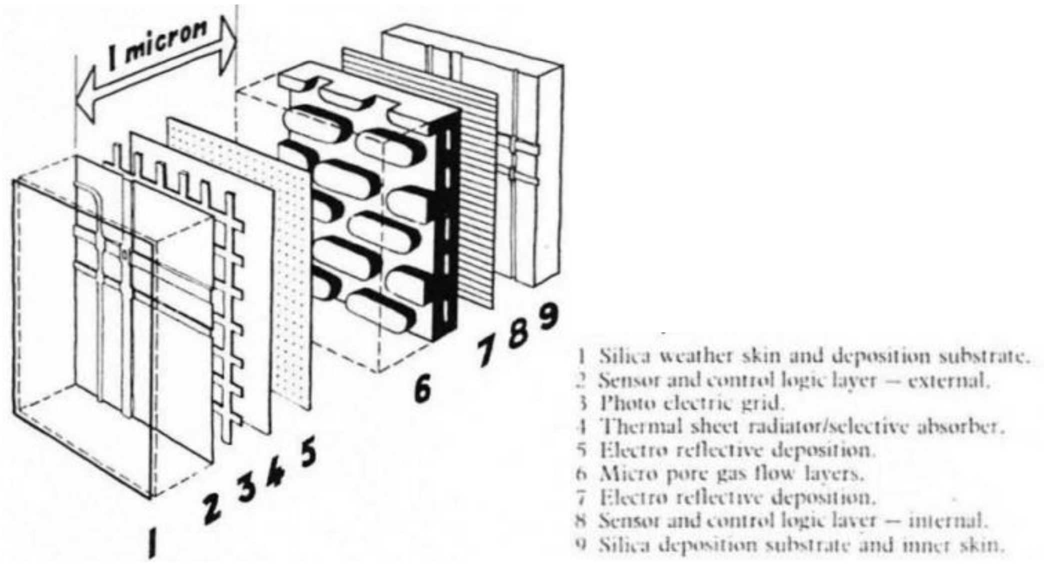


Figure 2.56: Concept of ‘A Wall for All Seasons” (Davies & Rogers, 1981)

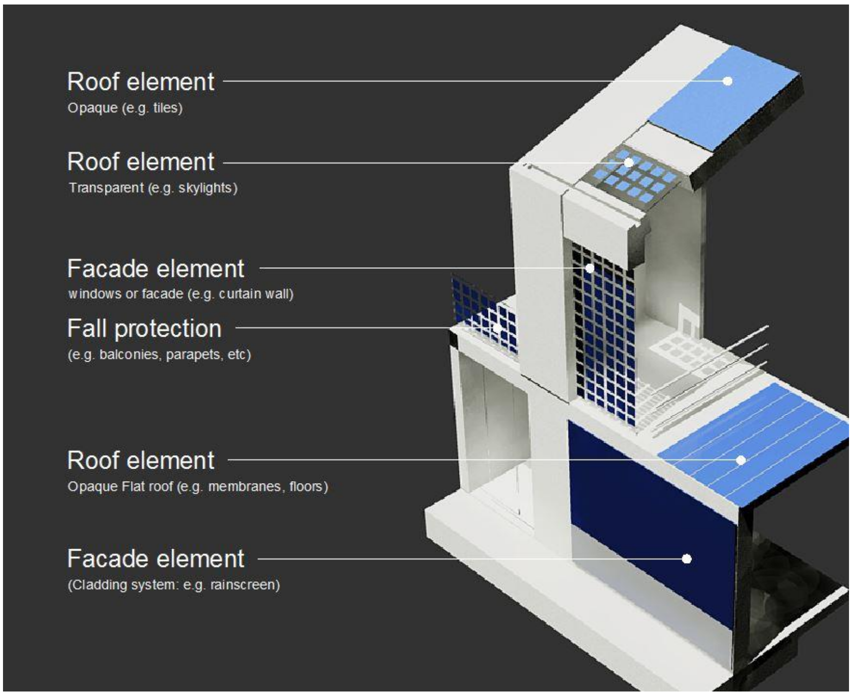


Figure 2.57: BIPV Utilization in Various Building Parts (URL 28)

PV's create differences: first, in terms of construction, PV systems integrated in the buildings should act just like roofing cladding and the traditional wall. As a result, they must consider all common issues.

Then some other specific aspects exist, which are usually capable of using the electricity produced, i.e.:

- Preventing self-shading
- Generating heat and ventilation
- Providing accessible routes for cables and connectors
- Maintenance.

Three principal design options for PV integration in building envelopes are (URL 26):

- Roof-based systems
- Facade systems
- Sunscreens and sunshades.

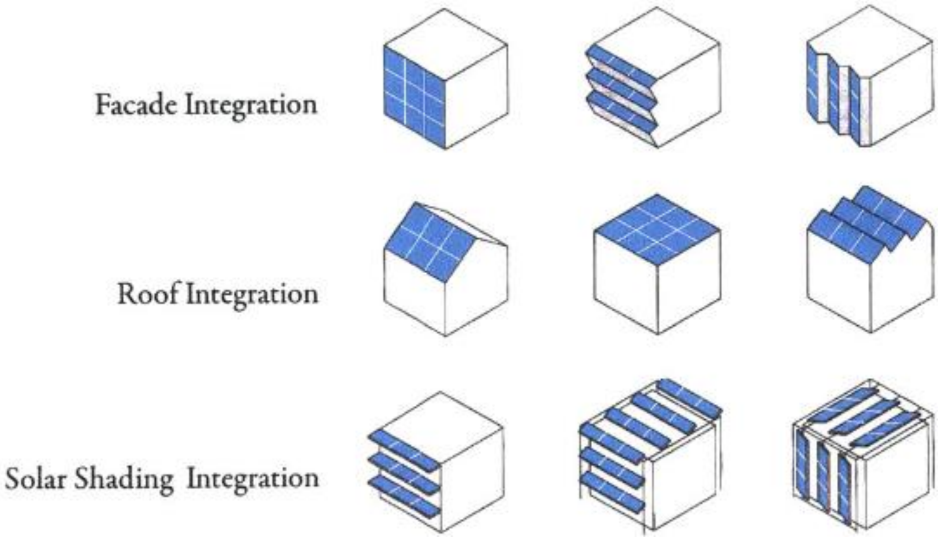


Figure 2.58: Design Options for Integration and Arrangement of PV in the Building (Arthur, 1995)

Once photovoltaic system is designed, it must be guaranteed that constructional integration has a direct relationship with architecture. Especially, PV installations can be seen more noticeably on the façade.

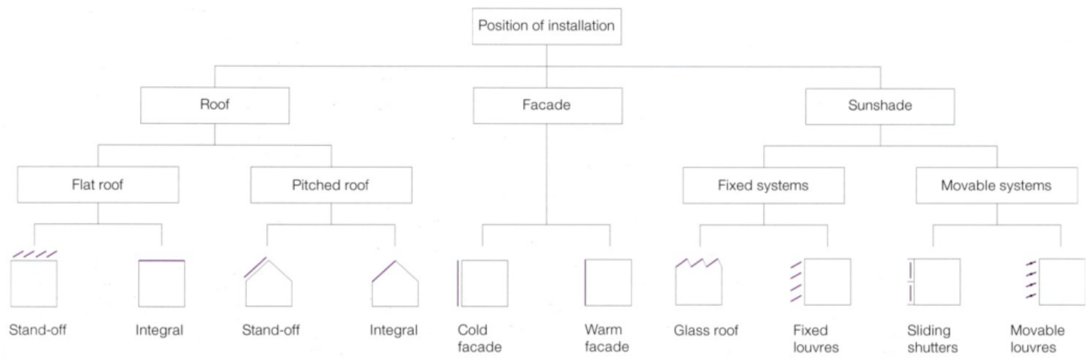


Figure 2.59: The Main Options for PV Installation on the Building Envelope Parts (Weller et al., 2010)

Table 2.8: General View of BIPV Utilization and Solutions (Heinstein et al., 2013)

Type of application / Type of product	Pitched Roofs	Flat Roofs	External Building Walls	Semi-Transparent Facades	Skylights	Shading Systems
Standard in-roof systems	√					
Semitransparent systems (glass/glass modules)				√	√	√
Cladding systems			√			
Tiles and shingles	√					
Flexible laminates		√				

Table 2.9: Comparative Assessment of Several BIPV Solutions (Fraile & Ciesielska, 2009)

Product	Specific Advantages	Specific Disadvantages	Applications	Key segments
Standard in-roof systems	■Suitable for old and new roofs ■ Well established application ■ Easy to Handle ■ Under the scope of the French and Italian BIPV definition ■ Very competitive ■ High efficiency performance	■ Limited aesthetic value due to level of visibility ■ Scope of application limited to certain roof Types ■ The multifunctional aspects of PV are not fully exploited	■ Pitched Roofs	Residential and Commercial buildings
Semitransparent system (glass/ glass module)	■ Most unobtrusive and possibly most aesthetic BIPV solution ■ Ideal suited for prestigious buildings with well-visible facades and skylights ■ Marginal daylight elimination/capacity to diversify light intake ■ Cell shapes can be attractive ■ With Thin Films cells they have uniform appearance, suitable for flush mounting	■ The units can be very heavy ■ The prices are normally high since they are usually tailor-made products ■ As they can be seamlessly integrated, the public may no notice the presence of PV modules ■ Difficulty in hiding the cables ■ Limited sizes and shapes of cells ■ Silver tabbing crosses the transparent spaces between cells	■ Semi-transparent Facades ■ Skylights ■ Shading Systems	Commercial and Public buildings
Cladding systems	■ Well suited if the PV system is to be recognized (green image owner) ■ Different colors and visual effects can be included ■ High efficiency systems	■ Lower system performance (due to design restrictions) ■ The lower parts of facades are normally not used due to possible shadows ■ Installation cost can be very high	■ External Building Walls ■ Curtain Walls	Commercial and Public buildings
Solar Tiles and shingles	■ Aesthetic solutions, mainly for residential pitched roofs ■ High-efficiency products ■ Very light products which eases the installation	■ Small unit size lead to longer installation time ■ Unfavorable cost-performance ratio ■ High risk of breakage	■ Pitched Roofs	Residential buildings Old buildings
Flexible laminates	■ Very lightweight (suitable for weak roofs) ■ Easy handling and installation ■ Low BOS cost ■ No roof penetration ■ Curved installations possible	■ It doesn't replace other functions of building components functions: BIPV status at stake ■ Very low efficiency which results in larger system areas	■ Flat and curved roofs	Commercial and industrial buildings (with large unused roofs)

2.2.8.1 Roof-Based Systems

Roofs offer various attractions as PV sites because (Nitta et al., 1994):

- They often do not have overshadowing (unshaded solar access).

- Integrating PV's functionally and aesthetically into a roof is easier than a wall.

- Some part of the cost is compensated by displacing roofing materials through PV materials.

- In order to have higher performance, roof slope is selected.

- A better placement and orientation of solar cells is possible by using flat roofs, and

- When a roof slope is almost desirable, the need and support frame cost is eliminated.

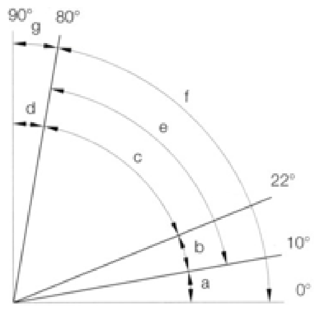
When a PV is mounted on the roof, some basic differences between flat and inclined roofs must be observed. Stand-off systems refer to the PV installations which are mounted over the existing roof. However, when PV modules are used instead of roof covering, providing a rainproof layer, the system is integrated.

Furthermore, roof surfaces are prior areas for PV placement and identified according to the related surface pitches' (Table 2.10). In general, flat roofs are built with a slope of 5°-10°, and based on guidelines and standards of German roofing trade, the slope must be at least 2%. Flat roofs are divided into three basic forms: cold roofs (in which air space is beneath roof covering), warm roof (with no air space), and inverted (upside-down) roof (with thermal insulation over waterproofing).

At angles more than 10°, there is a shallow sloped roof, and at angles bigger than 22°, the slope of the roof is steep. As it is mentioned below, sloped roofs are categorized having an angle between 10° and 80°. Another subdivision at an angle of 22° represents the minimum slope of the covering materials of the roof with a small format (slates, concrete or clay tiles) suitable for rainproof design. It is common to use transparent glass or opaque metal coverings for shallow sloped roofs. Glass or glazing PV's which are inclined to the vertical at an angle of >10° are categorized as overhead glazing. Constructions inclined to horizontal at the angles of 80° and 90° are categorized as facades. In such ranges, PV modules are categorized as vertical glazing. The overhead and vertical categories depend on different loads as well the risks associated with installation angle.

Table 2.10: Classification of Roof Areas and Related Allocation According to Building Legislation (Adopted from Weller et al., 2010)

Category	Roof Type	Angle allocation (°)
A	Flat roof	0-10
B	Shallow pitched roof	10-22
C	Steep pitched roof	22-80
D	Façade	80-90
E	Pitched roof	10-80
F	Overhang glazing	22-80
G	Vertical glazing	80-90



Depending on the type of constructional integration, rooftop PV systems are divided into integral and standoff systems. In standoff systems, there are separate supports for bearing the load of PV modules. In contrast, in an integral system, conventional roof covering is replaced by PV modules. Meeting the stability requirement is very important: every individual element of PV installation along with the entire installation should be stable. Especially in the existing roofs, the roof should be able to carry the excess loads, transferring them to other parts. There will be different possibilities concerning how BIPV system can be recognized in the roof's layout. These possibilities are given in the diagram that follows:

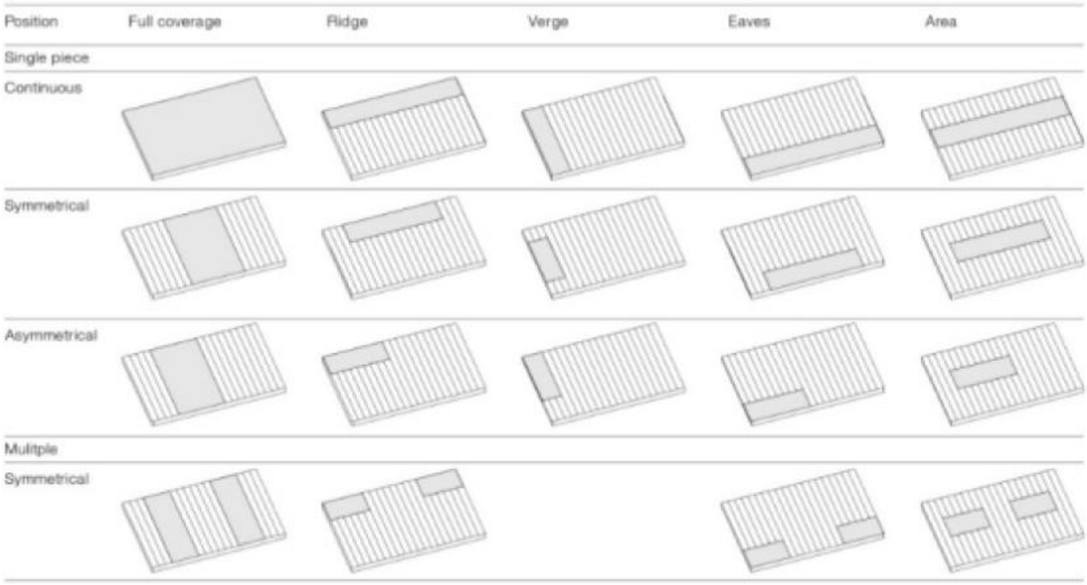


Figure 2.60: Several Configurations of PV Building Product within Roof or Façade (URL 26)

2.2.8.1.1 Ventilating Roof Systems

Ventilation in roof systems is expected to be easier than façade systems. In addition, any surplus heat gains, are probably less effective than those in façade systems provided that they are above occupancy height. If the roof design is inclined, the PV module can be installed onto a sub-frame on top of the roof structure. This is illustrated in Figure 2.70. By doing so, an air space (100 mm if practical) is created between the roof structure and the module. In many roofs with saw-toothed design, North lights will remove the heat.

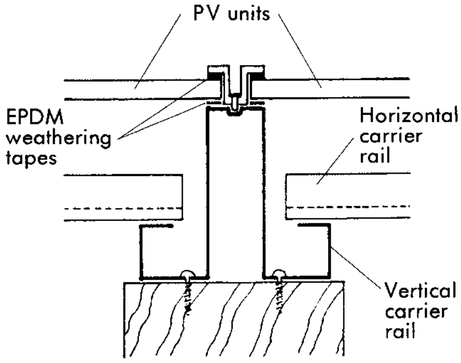


Figure 2.61: PV Roof with Ventilation

2.2.8.2 Façade-Based BIPV Systems

The potential of the façade is significant. Building facades are conventionally formed of walls, cladding, fenestrations and glazing as well as other structures such as balconies, shading devices and parapets. It is possible in any of these components to integrate PV's into the building, and if extended, the façade can be customized (Jelle, 2016). The main applications for BIPV façade are as follows: glazing, curtain walls, external or shading devices, and innovative applications (Bonomo et al., 2015). The classification of different facades is given in table 2.11 and table 2.12. Furthermore, among integration types, shading is the simplest because it is basically an add-on structure. However, it performs two functions, i.e., protecting excessive solar gain and generating power:

a) A rain-screen is added to traditional buildings in which PV is mounted as the external leaf. This external leaf of rain-screen covering protects the structure against rain, while the internal leaf is a protection against air (Scott et al., 1992).

b) Stick system which is, in fact, a kind of curtain wall made of lightweight materials is built on-site and requires scaffold. Vision or opaque panels can be replaced by PV modules. Metal frames having opaque and transparent panels are used in curtain-wall facades. A kind of PV module which is integrated with a curtain-wall has been produced to be used in Japan. It consists of glass, polycrystalline solar silicon cells, EVA, and aluminum base plate (Yoshino et al., 1997).

c) Unitized is another kind of curtain wall has factory-made units, and can be mounted on-site but without scaffold. In very tall building, this method has preference.

d) Another design with a high performance is the use of double-skin facades that come in various forms.

e) It is possible to use PV modules in atria and canopies, which are sloping or horizontal facades.

f) Glazing systems.

The systems used on facades are identified based on the thermal features that facades have, that is, cold and warm (single- and double-leaf, respectively) facades. If the façade is warm, integration is full; PV elements are integrated into insulating glass elements, fulfilling all functions of facades. If the façade is cold, mounting PV is either additional or acts as a substitute for weather-proofing.

Table 2.11: The Opportunities for PV Integration in Different Façade Systems (Adapted from Roberts & Guariento, 2009)

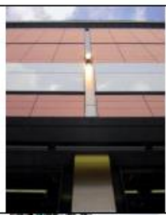
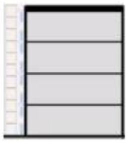
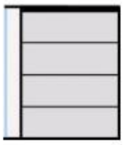
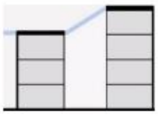
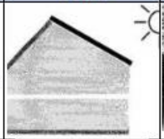
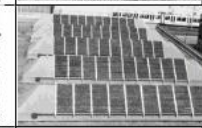
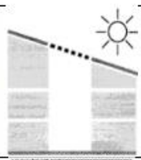
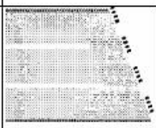
PV Integration Options in Different Façades	Schematic View	Examples	Description
1- Shading Systems			- The easiest type of PV integration - Composed of an add-on structure - Including dual function of solar gain control and power generation
2- Rainscreen Systems			- The Possibility of application to the construction of a traditional building - PV assumption as the outer leaf
3- Stick-system Curtain Wall			- A lightweight curtain wall type - Constructed on-site with scaffold support - The possibility of PV replacement with the opaque or vision panels
4- Unitised Curtain Walls			- Other types of curtain wall but with pre-fabricated units - The ability for installation on-site without scaffold - Priority method for high-rise buildings
5- Double-Skin Facades			- Design with high-performance embraces different form types
6- Atria and Canopies			- Utilization of PV modules on horizontal or sloped surfaces

Table 2.12: The Types and Opportunities for PV Integration in Different Roof/Façade-Based Systems (Adopted from Thomas et al., 2003)

	PV Position	Available System	Schematic View	Examples	Characteristics
Roof–based Systems	**Inclined Roof**	PV roof panels			-Combined with the roof structural system
	Roof with integrated tiles	PV roof tiles			-Roof tiles are familiar products and are likely to find easy acceptance
	Saw-toothed North light roof	PV panels			- Daylighting is allowed to enter interior spaces
	Curved roof	Opaque PV flexible substrate or rigid modules arranged on a curve			-Extends design possibilities
	Atrium	PV roof panels			-As for the inclined roof -Variations include part-glazing, part-opaque PVs and semi-transparent PVs
Facade Systems	**Vertical wall**	Curtain walling			-Standard, economical construction -PVs can be mixed, ie some being opaque and some semi-transparent
	Vertical wall with windows	Rainscreen cladding			-Rainscreen designs incorporate a ventilation gap which is advantageous in getting rid of heat; the gap can also be used for running cables.
	Inclined PVs with windows	Glazing or rainscreen cladding			-PV efficiency improved -The complexity of construction increased -Potential to provide shading of windows (if desired) but a degree of self-shading
	Inclined wall with windows	Glazing			-Potentially enhanced architectural interest -PV output improvement compared with a vertical wall -Less efficient use of building floor area
	Fixed sunshades	Glazing			- Can enhance architectural interest - Entails a loss of daylight
	Movable sunshades	Glazing			- Enhancement of architectural interest -Entails some light loss but less than with fixed shades. -Increased PV output compared with all fixed systems

2.2.8.3 PV Shades

PV panels are capable of being integrated into brise-soleils and awnings, and provide window shading. This way, a PV system is elegantly integrated into the building, especially wherever rooftop installation is not practical. In an appropriate design, it should be guaranteed that the panels have an optimal tilt for generating electricity and provide adequate shading. In populated areas in the city, the awnings mounted on the building's lower levels may receive considerable shading from the structures around. As with other external means of shading, minimizing thermal bridging and penetrations of air barrier in the awnings connected to the building must be considered. PV's can be used as fixed sunshades, providing protection for the building and users against excessive heat and generate at the same time. When movable sunshades are adjusted to solar altitude angle, the energy yield is improved (Hass, 1995).

Figure 2.62: Flexible Laminates PV (Up); PV Shades (Down) (Hass, 1995)

2.2.9 Design Concepts for PV in Construction

Energy subsystems of a building include the building envelope, technical services and the structure for bearing the load. Besides constructional integration, the architecture of active solar elements, which is exactly in the building shape, will be particularly substantial in the development of solar architecture in the future. At any rate, the harmony existing between the building and solar technology and the subsequent attractive architecture that, to a great extent, will determine the success and acceptance level of these technologies.

Distinguishing between three designing strategies is essential, i.e., addition, adaptation and integration (Figure 2.63). Furthermore, such classification is evident regarding the potential ways the photovoltaic modules are used in buildings' envelope.

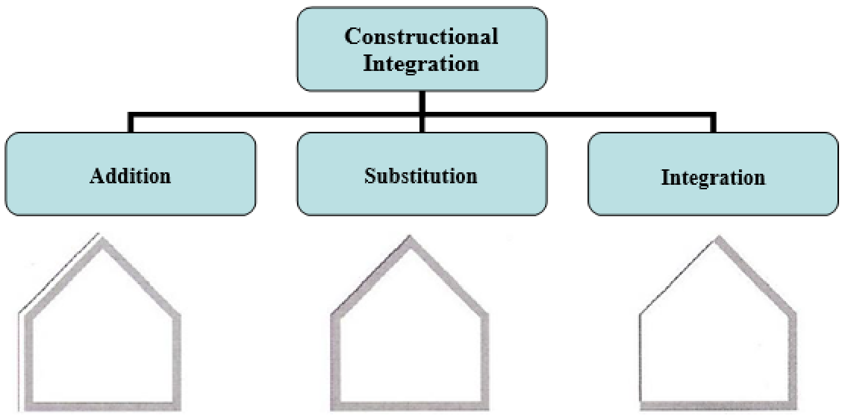


Figure 2.63: Various Options for Integrating Photovoltaics into the Construction of a Building (Weller et al., 2010)

2.2.9.1 Addition

Technically, the addition principle represents a kind of design in which no solar technology is used. Therefore, when solar technology is added, there is no concentration on the geometrical as well as architectural configuration of the building envelope, and the building is a structure that can support the structure of the solar technology. When the architectural integration is missing, components of solar technology will not fit to the building, and this, in turn, will have harmful effects on the appearance of the building. This will be evident when solar technology is mounted onto the buildings. In principle, adopting an additive approach will lead to undesirable solutions no matter how costly the element will be integrated into the building envelope.

2.2.9.2 Substitution (Adaption)

If the components for actively using solar radiation together with certain needs concerning orientation and without experiencing shadows, are integrated into the design and dominate it, this will involve planning and adjustment in several senses, in which the form and even the envelope of the building will change. Therefore, the building or parts of it must, to a great extent, be adapted to meet the needs of solar elements. So, this will improve the energy efficiency. Then using solar energy becomes a main criterion for the architectural design of the whole building. The solar elements and the building mutually depend on one another. This kind of integration has a high potential for the development of new architectural forms that can actively use solar radiation.

2.2.9.3 Integration

In this method, the solar elements are integrated into the building's architectural concept and the building: their dimensions, designs of vertical and horizontal connections and surfaces do not seem alien. Therefore, the solar elements are integrated into the building's three-dimensional shape. However, this can cause a decrease in the use of the existing solar radiation. Nevertheless, other functions and compact tiles with a high visual quality compensate this.

2.3 Building Form and its Relationship to Energy Efficiency

A building's form has a major impact on a building's functionality, energy efficiency, and occupant performance. The form of a building has an effect on its energy use (Oral & Yilmaz, 2003). It is described by two indicators: compactness (C), which is its surface area-to-volume ratio, and form factor (FF), which constitutes the strong relationship between the exposed surface areas and the treated floor areas (TFAs) (Thorpe, 2018).

Lin (1981) stated that, the building shape is recognized as the dependent factor for the building energy consumption. This matter is more important in the cold climates. In terms of heating, using the larger building envelope surface leads to more energy consumption; so, the minimum exposure surface would be one of the highest priorities for optimal form determination.

In the parametric research realized by Gratia and Herde (2003), a total number of parameters impacting the energy consumption studied in two office buildings in Uccla (Belgium) climate with the constant volume by two thermal programs of OPTI and TAS to optimize their energy and comfort performance. The preliminary analyses for six office building shapes with the same volume of $432m^3$ and 50% glazing ratio on the East/West walls comparing to the Southern walls indicated two separated different values of 40% and 24.9% for compactness and heating load between the most compact and less compact shapes respectively. The middle-size office building with 150 office cells, 5 floors and 2 orientations analyzed in 6 cases which involves non-insulated to strongly-insulated building. The results demonstrated that significance of the internal gain effect on cooling loads receives more degrees of importance than insulation effect which keeps the internal gain and solar insolation inside in summer regarding the exterior surfaces of the building shape.

Geletka and Sedlakova (2011) examined the impact of the building shapes on energy consumption for optimum design of energy efficient building and building load. They created two matrices (18*8) of building shapes of plans and elevations for simple and complex plans to find out the optimal shape regarding heat loss minimizing from the building exposure. The shape factor difference between the minimum and maximum ones-which is made of comparing these forms with the most compact form of cube with the fixed volume- was 88%. Also, six different shape scenarios of ground plan ratio to shape factor for various orientations and façade glazing ratios (0 to 100%) for an office building as a case study within the same volume of 42875m^3 and total heated floor area of 12250m^2-which is based on 3.5*3.5*3.5 modules- simulated parametrically by Design Builder program. The R^2 was 0.947. The results refer to the heat loss dependency on orientation and glazing ratios. Furthermore, the proved that appropriate forms to minimize heat loss regarding shape factor -from the best to worst- would be about cylinder (less jagged form), cubic (with less orientation impact on heating load) and rectangular. Shape factor impact on rectangular shapes by the ratio of 1:8 for ground plan to heating load is considerable as 10% while it is allocated as 20% for the remaining analyzed shapes, Hence, the effect of non-forgettable architectural characteristics must be considered on energy consumption.

According to the Pessenlehner and Mahdavi (2003) study on the building morphology, against size-dependent index of compactness, RC is shape-dependent and affects the heating loads. Also, unlike the compactness indices like characteristic length (lc) and RC, relative compactness (RC) is an appropriate indicator to define the shape compactness based on the subjective and intellectual classification. They tried to find out the relative compactness (RC) effect on the heating load and overheating through NODEM simulation program. So, 18 cubical elements (3.5*3.5*3.5m) -as the reference cube-were used to generate 720 morphological variances with the same volume of 771.75 m^3 but 12 shapes, 4 rotation towards North/East/South/West along with three levels of glazing ratios of (10%, 25%, 40%) by 5 various methods of distribution across the exterior volume in Vienna. Considering the given reference cube, relative compactness range for 12 selected shapes is in between 0.62 and 0.98. Their simulation results approved the minimum and maximum heating load for South-facing and North-facing glazing of the buildings respectively. Furthermore, correlation coefficient between RC and heating load is tangibly high (R^2=0.88), but RC interdependency with overheating is partly weak (R^2=0.59). Also, they confirmed that the lowest RC (=0.62) resulting highest value which is more than 3000 kWh/m3a for heating load. Also, to check the precision of the regression for heating load prediction, 5 different shapes with the same RC value of 0.86 selected for analyses. The results implied the reliable heating load value on geometry variant instead of the morphological attribute. The aberration ranges from the prediction for heating load and overheating are in between -15% to +10% and -80% to +130% respectively. Also, despite the lc which is volume-dependent, RC is not related to the volume. But the heating load is the function of both of them.

C and relative compactness (RC) are design performance indicators that affect heating load and overheating in building morphology. Whereas C is the ratio of the building envelope surface area to the heated internal volume (A/V), compared to its size-dependent index, RC is shape-dependent and affects heating loads.

Mahdavi and Gurtekin (2002) stated design performance indicators for space visualization and its utilization by designer to find out design variables and related performance characteristics. They recommended “Relative Compactness (RC)” concept for better understanding of relationship between its numeric values and subjective assessment of compactness for architectural shapes. Furthermore, RC introduced as the useful tool to derive the “characteristic length (l_c)” which is defined as the building volume ratio to its exterior surfaces. RC is an appropriate indicator to define shape compactness based on a subjective and intellectual classification. The correlation coefficient between RC and heating load is tangibly high, whereas RC interdependency with overheating is relatively weak. Furthermore, despite lc being volume-dependent, RC is not related to volume (Pessenlehner & Mahdavi, 2003). Also, in their empirical study, the relative compactness of the 14 shapes for one/two-story residential building calculated based on the equation (RCcube= 6* V^2/3 * A-1) V is the shape volume (m^3) and A is the shape area (m^2). Their calculated RC for the studied shapes was in the range of 0.49 and 0.98 while its correlation with the subjective evaluation presented R^2=0.965. Meanwhile, the linear regression of R^2=0.663 achieved regarding the relationship between subjective ranking and characteristic length. Finally, they identified that the improved design performance is carried out if needed changes applied to the design variables (Mahdavi & Gurtekin, 2002).

Lylykangas (2017) conducted a research which is focused on the shape effect on heating energy demand for conventional one/two-story single-family dwelling units of 150 m^2 in Helsinki, Finland; Goteborg, Sweden and Frankfurt, Germany to compare two-known shape factor definition based on the different passive house centers guideline in Germany and Sweden through the dynamic energy simulation software of

IDA. In Germany, shape factor is determined as the ratio of building envelope surfaces to the heated internal volume (A/V) which is relied on the building size. According to German Passive House Institute guideline, (A/V) ratio must be smaller than 0.8 m2/m3. While, Swedish Passive House Center (Passivhuscentrum) defined the shape factor (form factor) as the ratio of building exposure surfaces (A_{om}) to the heated floor area (A_{temp}) which is more reliable indicator to achieve successful compacted building shape. Afterwards, applying both architectural and technical variables in the early-phase design process, made considerable effects on heating energy demand. IDA simulation for various shapes and plan layouts demonstrated two different results for A/V and Aom/Atemp in the range of 0.7 to 1.00 and 2.25 to 3.75 respectively. Based on the results, A/V is not reliable index for heating energy demand calculation due to its diverse correlation between the increased internal height and heating energy demand against decreased A/V ratio. Since the efficiency status is linked to the treated floor area. A/V ratio can bot be used for architectural shapes. But it might be applied on 3D volume of absolute geometrical shapes for efficiency assignment. From the other hand, A_{om}/A_{temp} ratio -by good relation with the increased height and energy demand, specified the internal heat loss in association with floor area. Consequently, it could be acceptable for architectural volume performance due to utilization of better quantitative index of floor area in comparison with volume. Also, bad shape factor (less compacted shape) resulted in the low increased heating energy demand in Northern climate than the central part of European climate.

2.3.1 Building Envelope and BIPV Integration

Building shape is considered to be the most important item which affect the energy demand, energy consumption and thermal performance of the buildings. But also, provides solar insolation advantages for them (Ouarghi, et al., 2006; Depecker et al., 2001; Knowles, 1981). In addition, it affects the received solar radiation intensity and its whole energy consumption as well (Mingfang, 2002). Therefore, the building shape takes dual contradictory functions of pinpointing the available façade/roof surface areas for solar energy utilization and at the meantime energy losses due to its exposure surfaces (Pacheco et al., 2012). Thus, applying the optimum ratio of surface-to-volume would be helpful strategy in the early-stage design process (Neufert, 1995).

The building envelope offers opportunities for photovoltaic (PV) integration as a building integrated photovoltaic (BIPV) system in the exposed structure (Ritzenab et al., 2017) (Li et al., 2015). BIPV became noticeable in the late 1990s, and is the most promising solution to electricity generation. The multi-functional building component concept employs semiconductor PV modules for useful power and as PV integration into the building envelope by replacing the conventional materials on roofs, façades, windows, and sun shading elements (Shukla et al., 2016) (Agrawal & Tiwarim 2010). Additionally, it provides climatic protection, thermal/acoustic insulation, and carbon emission reduction of a building's footprint, while it generates power in response to the building's energy demand for utilization in the building itself; the power may be stored and fed into the electricity grid, while, simultaneously, the system adds value to the building (kim et al., 2017; Celik et al., 2015). The design principles of the BIPV system are similar to the PV system, with proper tilt angles based on the location's latitude and orientation toward the South (in the northern hemisphere) for maximum energy performance (Zomer & Rüther, 2017). Its performance is impacted by increased temperature, less or non-ventilation in the building envelope, non-optimal tilt angle, and azimuth (Maturi et al., 2014). It should be noted that challenges, such as partial shading, non-optimal tilt, and azimuth, impact the performance ratio (PR) negatively. For PV installation in partially shaded open areas, non-uniform performance of PV generation under realistic situations is expected. Consequently, less solar radiation on shaded modules results in power absorption and acts as a load (Celik et al., 2013). However, the shading effect on PV panels that arises from a building's configuration can be analyzed by appropriate simulation using the DesignBuilder software.

Presently, BIPV roof systems are preferred because of less shadowing, resulting in more power supply, while PV integration in façades is becoming increasingly more popular for aesthetical reasons (Osseweijer et al., 2017). However, roof-mounted and façade integrated technologies in the BIPV market make up 80% and 20%, respectively (Krawietz, 2011). In addition, depending on the local climate, solar yield availability, and mounting geometry, a BIPV roof-mounted system output can cover 14.5% to 58% of a building's energy demand (Zhang & Mirzaei, 2017).

Hachem et al. (2012) identified the effect of the most important design parameters covering geometric shapes on the energy performance of typical two-story residential building and its limited neighborhood in the cold climate zone of Montreal, Canada in the mid-latitude of 45°N. The relationship between the design parameters and performance criteria including the consumed heating/cooling energy and BIPV electricity generation presented in a matrix as decision-helpful tool for optimal performance selection. The specified key design parameters of aspect ratio (the ratio of South-facing to lateral dimension) and South-facing orientation for convex shapes to increase the possible solar radiation to cover the heating demand and BIPV electricity production. While, the additional parameters include depth ratio and shading ratio has an importance regarding design parameters in non-convex shapes. Furthermore, the reduction in BIPV system performance-comparing to the South façade- for South façade deviations of 45° and 60° towards East or West is about 5% and 12% respectively. Also, they approved that the optimal tilt angle for BIPV performance would be approximately closer to the location latitude.

In the other research, Hachem et al. (2011) explored the effect of seven form types on the solar potential of the South facades and BIPV potential in South-facing roof by the aid of Energy-Plus simulation program for various shapes of two-story residential buildings in Montreal, Canada. According to the results, major parameters as the geometries of shading and shaded facades with affiliated dimensions must be identified due to their great influence on the exploited solar radiation. The reduction rate for annual power generation by BIPV system for the L-shape comparing the reference shape of rectangular is 3%. Also, in the L-shape buildings employing roof rotation of 30° from South towards East or West, enhanced the production rate of solar electricity which is beneficial to shift the peak generation for 3 hours. So, the energy performance of the existing buildings, in terms of significant renovation, must be upgraded to satisfy the minimum requirement.

In other words, almost all the energy requirement, calculated annually, is supplied by clean energy sources on the building site itself (Chatzipanagi et al., 2016). Therefore, it is expected that the BIPV application will accelerate in the years ahead. Furthermore, the key factors, with high priority for integration, in the BIPV system are architectural aesthetics, function, technology, cost, and cost-benefit. Research suggests that façades are more critical than roofs in high latitudes in the northern hemisphere due to the lower annual solar altitude (Biyik et al., 2017).

In the literature review, none of the studies focused on the contribution of interior and exterior building surfaces and their possible relation to the energy demand inside and the generated solar energy on the envelope, respectively. Additionally, FF, which constitutes the relationship between the envelope surface area (A) and the TFA, is an advantageous and helpful tool for designers and decision makers in the building sector for finding the needed heated floor area inside and the exposed surface area for PV integration into façades and/or roof area outside to meet the energy requirements. Therefore, it makes sense to use FF as a parameter in the early-stage design of the building form, along with C. Thus, the development of a new approach to assess the energy performance of BIPVs on the building surfaces by determining the form types that achieve a high electricity production percentage is indispensable.

2.4 Standards about Energy Efficiency and PV Utilization in Architecture

2.4.1 Passive House Standard (PHS)

The PHS is one of the pioneering building standards that expanded globally for energy efficiency assessment and rating. Also referred to as the Passivhaus standard, it aims to provide a building with an acceptable and even improved thermal comfort and indoor air quality at minimum energy demand (Feist et al., 2005). It is not only for houses—it can also be used for all building types, including very low-cost buildings. The energy performance of the first PHS building, which was constructed as a prototype in 1991 in Darmstadt, Germany, was 90%, exhibiting a very high energy efficiency compared to the conventional construction (Dalben et al., 2019). There are five main principles for this ultra-low energy building performance standard (see Figure 2.73) (Müller & Berker, 2013): a) superinsulation, b) thermal-bridge-free design, c) Passive House windows, d) airtightness, and e) mechanical ventilation with heat recovery system (MVHR).

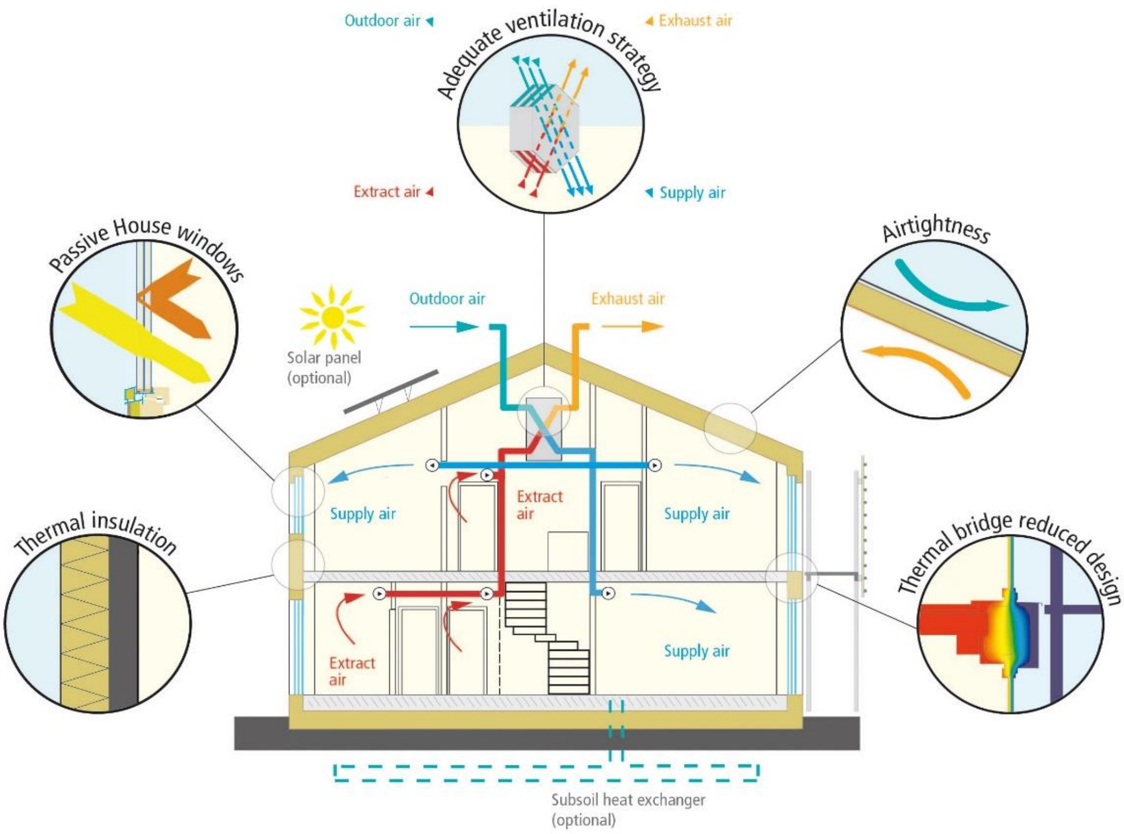


Figure 2.64: Five Main Principles to be Used in Passive House Standard (PHS) (URL 29)

Additionally, the general design criteria for PHS are described in Table 2.13.

Table 2.13: General Characteristics for Passive House Standard (Truonga and Garvieb, 2017)

Parameter	Unit	Maxim
Heating demand	kWh/m2/a	15
or Heating load	W/m2	10
Cooling and dehumidification	kWh/m2/a	15
or Cooling load	W/m2	10
alternatively, Frequency of	%	10
Airtightness (n50)	ACH	0.6
Primary energy demand	kWh/m2/a	120

However, based on economic and technical considerations, the essential design criterion to meet this standard for different building types is the entire specific primary energy demand (SPED), which must not exceed 120 kWh/m2 annually (Lewis, 2014). The SPED is the total primary energy demand for space heating and cooling, domestic hot water, dehumidification, auxiliary, and household electricity divided by the floor area (Truonga and Garvieb, 2017).

Truonga and Garvie (2017) studied on the one-story passive house in Canberra, Australia with the internal surface area of 127 m^2 based on Passive House Standard (PHS) and related utmost energy efficient key variants to demonstrate its high-performance and occupant comfort. The project adoption with PHS criteria carried out by the energy simulation tool called Passive House Planning Package (PHPP) which determined which specified the anticipated performance is below the limits. The annual energy performance monitoring emphasized a significant reduction of 64% and 62% in energy consumption compared to Canbera and Melbourne Houses. Also, since the total energy consumption was only 12% of the estimated value, its high efficiency based on PHS approved (Truonga and Garvie, 2017).

2.4.2 EN 50583 Standard: Photovoltaics in Buildings

The European standard EN 50583 for BIPV that applies to photovoltaic modules used as construction products, was published in 2016 (Ferra et al., 2017). This new standard consists mainly of the compilation and modification of existing standards related to BIPV. To be suitable for building integration, PV products must fulfil both the standards of the PV sector and the construction sector as presented in Table 2.14 (Osello et al., 2017).

Table 2.14: Electrical and Building Reference Standards for PV Modules (URL 30)

PV Module Standards	Building Standards
IEC International Electrotechnical Commission	**ISO** International Organization for Standardization
CENELEC European Commission for Electrotechnical Standardization	**CEN** European Committee for Standardization
CES Comite Electrotechnique Suisse	**SIA** Schweizerische Ingenieur-und Architekten-Verein

This standard is addressed to manufacturers, planners, system designers, installers, testing institutes and building authorities. EN 50583 does not apply to concentrating or building-attached photovoltaic modules. This document addresses requirements on the PV modules in the specific ways they are intended to be mounted but not the mounting structure itself (URL 31).

The EN 50583 standard has two parts:

- Photovoltaics in buildings – Part 1: BIPV modules
- Photovoltaics in buildings – Part 2: BIPV systems

2.4.2.1 EN 50583-Part 1: BIPV Modules

Part 1 applies to photovoltaic modules used as construction products. It focuses on the properties of PV modules which are relevant to the essential building requirements as specified in the Construction Product Regulation CPR 305/2011, and the applicable electro-technical requirements as stated in the Low Voltage Directive (LVD) 2006/95/EC or CENELEC standards.

According to EN 50583 part 1, BIPV modules are considered to be building-integrated if the PV modules form a construction product providing a function as defined in CPR 305/2011. Thus, the BIPV module is a prerequisite for the integrity of the building's functionality. If the integrated PV module is dismounted (in the case of structurally bonded modules, dismounting includes the adjacent construction product), the PV module would have to be replaced by an appropriate construction part (URL 30).

The fact that BIPV modules have to comply with requirements from two separate backgrounds (CPR and LVD) has led EN 50583 to be structured in three hierarchic levels of requirements (see Table 2.15).

Table 2.15: Levels of Differentiations EN 5058 (URL 31)

Level 1	General requirements for all BIPV resulting from requirements of the Low Voltage Directives and the Construction Products Directive of the European Union
Level 2	Requirements resulting from panel material (e.g., glass)
Level 3	Requirements resulting from panel mounting location within the building (5 mounting categories are differentiated)

● **Level 1:**

- The electrical requirements are relevant for all kinds of BIPV modules regardless of their technology and composition.

- The building related requirements are differentiated regardless of their technology but depending on whether the modules do contain glass or not.

● **Level 2:**

- Only for the modules that do contain glass, general requirements for all modules regardless of their location within the building are formulated.

- Only for the modules that do not contain glass, requirements are formulated regardless of their location within the building but according to their backsheet (water proofing polymer or metal sheet).

● **Level 3:**

Only for the modules that do contain glass, the categories A to E are specified that differentiate additional requirements for the modules according to the location within the building in which they are intended to be used (see Table 2.16).

Table 2.16: Mounting Categories A-E as Defined in EN 50583 Standard (URL 32)

Category A	**Sloping, roof-integrated, accessible from within the building** The BIPV modules are installed at a tilt angle between 0° and 75° including horizontal with another building product installed underneath	
Category B	**Sloping, roof-integrated, not accessible from within the building** The BIPV modules are installed at a tilt angle between 0° and 75° including horizontal.	
Category C	**Non-sloping (vertically) envelope-integrated, not accessible from within the building** The BIPV modules are installed at a tilt angle between and including both 75° and 90° with another building product installed behind.	
Category D	**Non-sloping (vertically) envelope-integrated, accessible from within the building** The BIPV modules are installed at a tilt angle between and including both 75° and 90°.	
Category E	**Externally-integrated, accessible or not accessible from within the building** The BIPV modules are installed to form an additional functional layer exterior to its envelope (e.g., balcony balustrades, shutters, awnings, louvers, brise soleil etc.).	

2.4.2.2 EN 50583-Part 2: BIPV Systems

Part 2 defines photovoltaic systems as building-integrated, if the PV modules they utilize fulfil the criteria for BIPV modules as defined in EN 50583-1 and thus form a construction product providing a function as defined in the European Construction Product Regulation CPR 305/2011. PV systems covered by part 2 of the standard are subjected to the same hierarchy levels as PV modules (see part 1). For systems containing glass, the mounting categories are the same as those defined in part 1 of the standard.

Part 2 of EN 50583 standard includes a specific test for BIPV roofs in category A (therefore only modules containing glass). The test evaluates the resistance to wind-driven rain of a BIPV pitched roof system including a kit of discontinuously laid BIPV modules in combination with adjacent mounting-relevant fixtures, sealants, joints and connections to regular surrounding roofing/building components (URL 30).

The results have shown that even if deviations exist between photovoltaic standard and building standard requirements, the EN 50583 provides a good compromise for the certification of BIPV products. Nevertheless, for some innovative configurations of products, some adaptations of standard tests or proposals of complementary standard tests are necessary.

Chapter 3

ANALYSES ABOUT BIPV FORM FACTOR AS AN APPROACH IN TERMS OF ENERGY EFFICIENCY

Building form and envelope surfaces play a significant role in energy performance assessment and the energy potential generated by the BIPV concept in early-stage design. The research is carried out in four sections: form organization, criteria (calculation methodology), analysis results, and validation of results. The objective is to determine the relationship and correlation between the generated energy on the exposed surfaces and the TFA to meet energy demand according to the PHS (Figure 3.1).

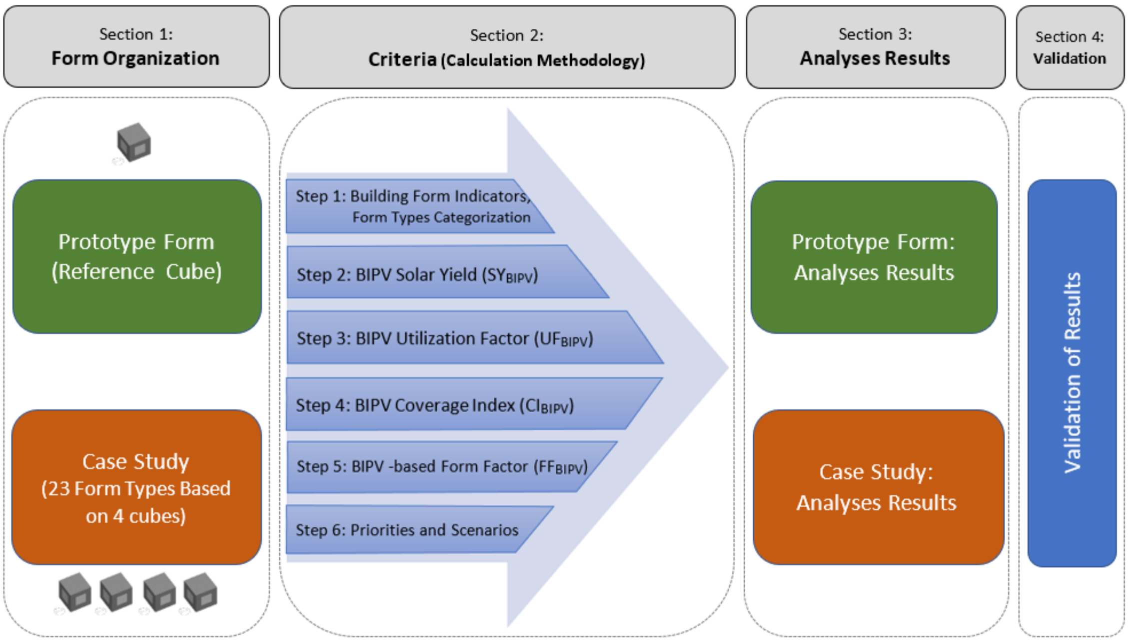


Figure 3.1: BIPV Approach Development (Author, 2021)

According to the BIPV approach development (figure 3.1), first, the prototype form is used as a reference cube for analysis through the six steps of criteria in section 2. Second, after establishing twenty three form types based on the four cubes, the process is repeated. In section 3, an analysis of the results related to the priorities and scenarios for both the prototype form and the case study is carried out. In section 4, the resulting FF_{BIPV} values for the case study are validated by the preliminary results of the prototype form.

3.1 Form Organization

Form organization comprises two parts: a reference cubic building model as the prototype form and a case study that includes twenty-three forms based on different configurations of the four prototype forms employed, which meet the requirements of the PHS. It is assumed that the prototype form and case study form types are located in the cool temperate climate of Tabriz, Iran, at a latitude and longitude of 38.13° N and 46.28° E, respectively. All of the form types have the same double-glazed windows in all orientations, where the optimal window-to-wall ratio (WWR) in each direction is 30% for Tabriz (Nasrollahi, 2009). Additionally, it must be noted that the construction specifications for the prototype form, including building materials, heat loss/gain, etc., are in accordance with the PHS.

3.1.1 Prototype Form (Reference Cube)

A reference cubic building form (3*3*3 m, WWR=0.3), based on the international PHS, is implemented as a prototype form to test the approach for possible PV system integration into the vertical and/or horizontal surfaces of six orientations: North, East, South-15°, South, South+15°, and West (Figure 3.2).

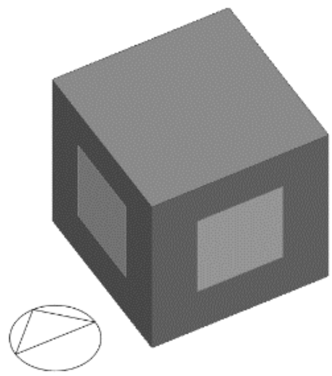


Figure 3.2: Prototype Determination Based on Cubic Module (Length=3m, WWR=0.3) (Author, 2021)

3.1.2 Case Study

The case study, which comprises twenty-three form types, resulted from various configurations of the four reference cubic forms, including attached/detached, square, rectangle, L, and T shapes, with constant volume; consequently, the energy consumption and generation are verified based on the PHS for the location of Tabriz, Iran in the Northern hemisphere. Additionally, a WWR of 0.3 is applied to all the façades, while the shading effect in the detached forms is avoided (Figure 3.3).

3.2 Criteria (Calculation Methodology)

The main criteria for the form parameters and ratios are employed in the calculation methodology in the six steps, and include the building form indicators FF and C, BIPV solar yield (SY_{BIPV}), BIPV utilization factor (UF_{BIPV}), BIPV coverage index (CI_{BIPV}), BIPV-based form factor (FF_{BIPV}), and priorities and scenarios. These criteria are used both for the prototype form modeling and for the twenty-three generated form types in the case study (Figure 3.1, 3.2, and 3.3).

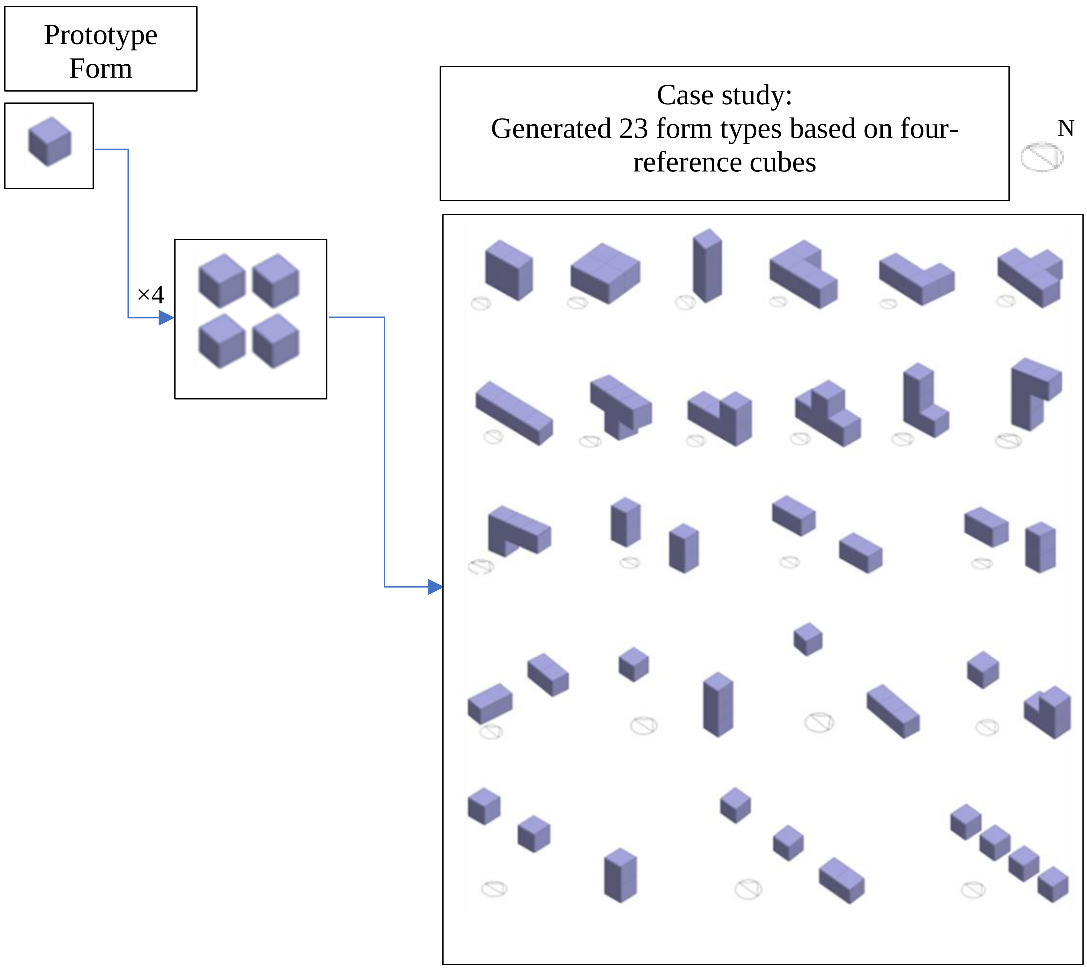


Figure 3.3: Case Study Comprises Twenty-Three Form Types Developed from Four Reference Cubes (Author, 2021)

3.2.1 Building Form Indicators (Form Type Categorization)

Each building form includes important indicators that are derived from building morphology. However, these indicators depend on the main characteristics of the building form, such as A, V, GFA, and TFA. Additionally, due to the thickness of the exterior walls (20 percent of GFA), it is assumed that TFA is 0.8 of the GFA. Thus, the resulting effective indicators are as follows:

- A/GFA: the ratio of the thermal envelope area to ground floor area
- FF: the ratio of the thermal envelope area to the TFA (A/TFA)
- C: the ratio of the thermal envelope area to the form volume (A/V).

First, these indicators are assigned to the prototype form (reference cube), and then to the twenty-three generated form types categorized into six groups in the case study. However, FF remains the main characteristic in all the categories.

3.2.2 BIPV Solar Yield (SY_{BIPV})

The global solar radiation on the collector planes for the six building azimuths, North (0°), East, South (180°), West, and the South façade deviation of 15° towards East or West (South ±15°), and the tilted surfaces at the Northern hemisphere in the cool temperate climate of Tabriz, Iran, are simulated using the DesignBuilder software (version 5.03.7) to assess the solar yield potential for the BIPV system (SY_{BIPV}) and its performance for the prototype form and case study (23 form types) (Figure 3.3.), based on a WWR of 0.3. The simulation process is based on equation 2.

$SY_{BIPV} = (A_{BIPV} * \eta * Gt)$ (Wiginton et al., 2020) (2)

Where:

SY_{BIPV}: Solar yield potential of BIPV

A_{BIPV}: BIPV surface area (m^2)

Gt: Total solar radiation incident on PV array (W/m^2)

η: PV module conversion efficiency.

A constant electrical conversion efficiency (η) of 12% for PV is employed in the subsequent simulations. This efficiency is based on a nominal PV efficiency of 16% and a PV system performance ratio of 0.75; η is the product of these two factors (0.16*0.75=12%) (Pelland & Poissant, 2006). In addition, mono-crystalline silicon (mono c-Si) technology is used for the PV panels. It should be noted that, due to the various azimuths and tilt angles of the exposed surfaces in pure building forms, such as the cubic model, the solar yield on different envelope surfaces is not equal. Therefore, the BIPV area for producing a certain amount of energy is not be the same for all the surfaces. Of all the envelope surfaces in the northern hemisphere, the North façade solar yield value is extremely low (existing in the early mornings and late afternoons) and may not be considered. There are only three effective vertical surfaces: the South, West, and East surfaces (depending on the orientation), plus the horizontal surface of the roof, which is the most important.

3.2.3 BIPV Utilization Factor (UF_{BIPV})

The BIPV utilization factor (UF_{BIPV}) is defined as the ratio of the BIPV solar yield for electricity generation on the roof or façades to the total primary energy demand (the product of the TFA and the SPED of 120 kWh/m^2) for the different azimuths, whereas the WWR of 0.3 is applied for the vertical surfaces. Therefore, the UF_{BIPV} for the façade surfaces in the six azimuths and the roof surfaces is given by Equation 3.

$$UF_{BIPV\ (Façade)} = (SY_{BIPV\ (Façade)} * (1-WWR)) / (TFA*SPED) \qquad (3)$$

$$UF_{BIPV\ (Roof)} = SY_{BIPV\ (Roof)} / (TFA*SPED)$$

Where:

$UF_{BIPV\ (Façade)}$: utilization factor for the BIPV system in the façade

$UF_{BIPV\ (Roof)}$: utilization factor for the BIPV system in the roof.

Additionally, the UF_{BIPV} is about the efficient use of the BIPV system on suitable building surfaces or optimal azimuth to meet the SPED. Depending on the BIPV solar yield, which is related to the available BIPV area, the UF_{BIPV} can vary. For more solar yield than the SPED for the TFA for any surface, the UF_{BIPV} would be bigger than 1; for instance, in Table 3.2, the UF_{BIPV} value for vertical surfaces, such as façades, is less than 1, whereas it is more than 1 for horizontal surfaces, such as a roof. In other words, for buildings with the same volume, meeting the SPED requirements in low-rise building forms with high roof areas is more easily achieved, and the related UF_{BIPV} is more than 1, compared to vertical buildings with low roof areas.

3.2.4 BIPV Coverage Index (CI_{BIPV})

The BIPV Coverage Index (CI_{BIPV}) is defined as the percentage of the total BIPV area on a façade or roof (A_{BIPV}) relative to the entire envelope surface area (A_{BIPV}) required to meet the SPED requirements for the TFA. Furthermore, it is the inverse of the UF_{BIPV}. Hence, the BIPV coverage index (CI_{BIPV}) can be used for rating the BIPV efficiency level which is insufficient for this step.

BIPV Coverage Index $(CI_{BIPV})=A_{BIPV}/A_{Envelope} = 1/UF_{BIPV}$

3.2.5 BIPV-Based FF (FF_{BIPV})

The FF_{BIPV} is the most important parameter for assessing the efficiency level of BIPV utilization, and causes the relation between the total sum of the available BIPV areas on the forming envelope (A_{BIPV}) and the TFA to meet the primary energy demand based on the PHS. Its character is similar to that of the general FF; however, its value is affected by azimuth variation:

$FF_{BIPV\ (Forming\ Envelope,\ Azimuth)} = A_{BIPV\ (Forming\ Envelope,\ Azimuth)}/TFA$

Therefore, it is similarly determined for façade and roof with respect to the given azimuth:

$FF_{BIPV\ (Façade,\ Azimuth)} = A_{BIPV\ (Façade,\ Azimuth)}/TFA$

$FF_{BIPV\ (Roof)} = A_{BIPV\ (Roof)}/TFA$.

Furthermore, the optimal FF_{BIPV} is obtained through the organization of various scenarios based on a combination of the priorities of the available exposed surfaces. By calculating a given solar yield received on any envelope surface of the building form, the required envelope surface area for the PV integration to cover the partial/full SPED will be achieved. If the exposure surface area is not sufficient for the BIPV system, additional surface areas of the other façades or roofs will be required for combination.

3.2.6 Priorities and Scenarios

Generally, each of the exposed surfaces (except roof surface) with BIPV potential cannot cover the SPED by itself. Therefore, it is necessary to combine two or even more BIPV façade surfaces for this purpose. Since the FF_{BIPV} depends on a combination of different façades or façades and roof, different configurations of scenarios as priority combinations of the BIPV surfaces help to find the best scenario with the minimum FF_{BIPV} and BIPV area to meet the SPED requirement based on the PHS. Therefore, based on the façade priorities, their BIPV coverage percentages will be different, and are categorized under six scenarios. Each of the six scenarios is based on a combination of two priorities (P1+P2) for BIPV coverage. The first priority (P1) indicates that the specified façade with the full BIPV coverage area (100%) is insufficient to meet the SPED requirement. Therefore, the second priority (P2) will provide the rest of the required BIPV area on the other façades/roof to meet the 120kWh/m^2/yr SPED requirement. Incorporation of P1 and P2 in each scenario leads to the determination of distinct FF_{BIPV}s for each configuration as a useful tool to specify the equivalent required BIPV area on the forming envelope of façade/roof of the TFA in relation to the SPED requirement. Consequently, the best-case scenario results in a minimum FF_{BIPV} for the building form envelope.

3.3. Analysis Results (Presentation)

3.3.1. Prototype Form Analysis Results

The analysis of the form indicators for the prototype form type includes the A/GFA, C, and FF presented in Table 3.1 and Figure 3.3.

Table 3.1: Main Characteristics of the Prototype Form (Author, 2021)

Length (L)	3 m
Envelope Area (A)	54 m^2
Internal Volume (V)	19.3 m^3
Window to wall Ratio (WWR)	0.3
Ground Floor Area (GFA)	9 m^2
Envelope Area to Ground Floor Area (**A/GFA**)	**6**
Treated Floor Area (TFA)	7.2 m^2
Compactness (C)	2.8 m^{-1}
Form Factor (FF=A/TFA)	**7.5**
Specific Primary Energy Demand (SPED)	≤120 kWh/m^2/yr
Total Primary Energy Demand (SPED*TFA)	120 * 7.2= 864 kWh/yr

For the prototype form, the DesignBuilder program is employed to calculate the BIPV solar yield (SY_{BIPV}) potential on the roof and façades for the six azimuths (N, E, S, W, and S±15°). The roof solar yield ($SY_{BIPV\ (Roof)}$) is twice that of the South façade, while it is approximately four times higher than that of the North façade (Table 3.3). Since the solar yield and UF_{BIPV} are directly related, the ratios are proportional. In addition, the North façade efficiency for the BIPV solar yield is approximately half that of the South façade. The least UF_{BIPV} value of 0.46 is for the North orientation, which translates into approximately two times more BIPV area to meet the SPED requirements than the South orientation (value of 0.88) (see Table 3.2).

Table 3.2: BIPV Solar Yield (SY_{BIPV}), BIPV Utilization Factor (UF_{BIPV}), and BIPV Coverage Index (CI_{BIPV}) in Different Façade Orientations (Windows are Excluded). The Roof Surface and North Façade Orientations Receive the Best and the Worst Values, Respectively, for These Three Criteria (Author, 2021)

Surface/ Orientation	**SY_{BIPV}**	**UF_{BIPV}**	**CI_{BIPV}**
Roof	1507.35	1.75	0.57
South-15°	764.25	0.89	1.12
South (180°)	754.32	0.88	1.14
South+15°	745.16	0.86	1.16
East	676.66	0.78	1.28
West	580.73	0.67	1.49
North (0°)	398.38	0.46	2.17

Regarding the CI_{BIPV}, the table indicates that 57% of roof area is required for PV integration without a need to combine with other façade surfaces, while the North façade requires more than twice its surface area (217%) for this purpose. Therefore, the North façade would be the worst surface priority for BIPV implementation, as well as the worst one for combination with other surfaces as a second priority for other façades.

The required surface area for PV integration in each façade and roof surfaces is calculated to check their SPED performance. Except the roof surface area, none of the façade areas could meet the SPED by itself. Table 3.3 presents six possible scenarios based on façades to determine the FF_{BIPV}, as a useful tool to specify the equivalent required BIPV area for the SPED requirement on the form envelope of façade/roof in relation to the TFA.

Table 3.3: BIPV-Based Form Factor (FF_{BIPV}) According to the Surface Combination Priorities in the Prototype Model (WWR=0.3, Priority1=P1, Priority2=P2) (Author, 2021)

Scenario 1			*Scenario 2*			*Scenario 3*			*Scenario 4*			*Scenario 5*			*Scenario 6*		
South-15° based Facade (P1 + P2)			South-based Facade (P1 + P2)			South+15° -based Facade (P1 + P2)			East-based Facade (P1 + P2)			West-based Facade (P1 + P2)			North-based Facade (P1 + P2)		
P1 Area (%) (P1: South-15° Facade)	P2 Area (%)	$FF_{BIPV} = A_{BIPV\,(P1+P2)}$ /TFA	P1 Area (%) (P1: South Facade)	P2 Area (%)	$FF_{BIPV} = A_{BIPV\,(P1+P2)}$ /TFA	P1 Area (%) (P1: South+15° Facade)	P2 Area (%)	$FF_{BIPV} = A_{BIPV\,(P1+P2)}$ /TFA	P1 Area (%) (P1: East Facade)	P2 Area (%)	$FF_{BIPV} = A_{BIPV\,(P1+P2)}$ /TFA	P1 Area (%) (P1: West Facade)	P2 Area (%)	$FF_{BIPV} = A_{BIPV\,(P1+P2)}$ /TFA	P1 Area (%) (P1: North Façade)	P2 Area (%)	$FF_{BIPV} = A_{BIPV\,(P1+P2)}$ /TFA
S-15° 100%	N 25%	S-15° +N 1.09	**S 100%**	N 27%	S+N 1.11	**S+15° 100%**	N 30%	S+15° +N 1.14	**E 100%**	N 47%	E+N 1.29	**W 100%**	N 71%	W+N 1.50	**N 100%**	W 80%	N+W 1.58
S-15° 100%	W 17%	S-15° +W 1.02	**S 100%**	W 19%	S+W 1.04	**S+15° 100%**	W 21%	S+15° +W 1.06	**E 100%**	W 32%	E+W 1.16	**W 100%**	E 42%	W+E 1.24	**N 100%**	E 69%	N+E 1.48
S-15° 100%	E 15%	S-15° +E 1.01	**S 100%**	E 16%	S+E 1.01	**S+15° 100%**	E 18%	S+15° +E 1.04	**E 100%**	S 25%	E+S 1.09	**W 100%**	S 37%	W+S 1.20	**N 100%**	S 61%	N+S 1.41
S-15° 100%	R 7%	S-15° +R 0.96	**S 100%**	R 7%	S+R 0.96	**S+15° 100%**	R 8%	S+15° +R 0.98	**E 100%**	R 12%	E+R 1.03	**W 100%**	R 19%	W+R 1.11	**N 100%**	R 31%	N+R 1.26

It should be noted that, apart from utilizing the roof as a first priority, which is self-sufficient to meet the SPED, among the four scenarios presented in Table 3.3 and Figure 3.4, the best combination priority is the incorporation of the South-based façade with the roof surfaces (S+R) in Scenario 1, with a FF_{BIPV} of 0.96, whereas the worst one is the North-based façade together with the West façade (N+W) in Scenario 6, with a FF_{BIPV} of 1.58.

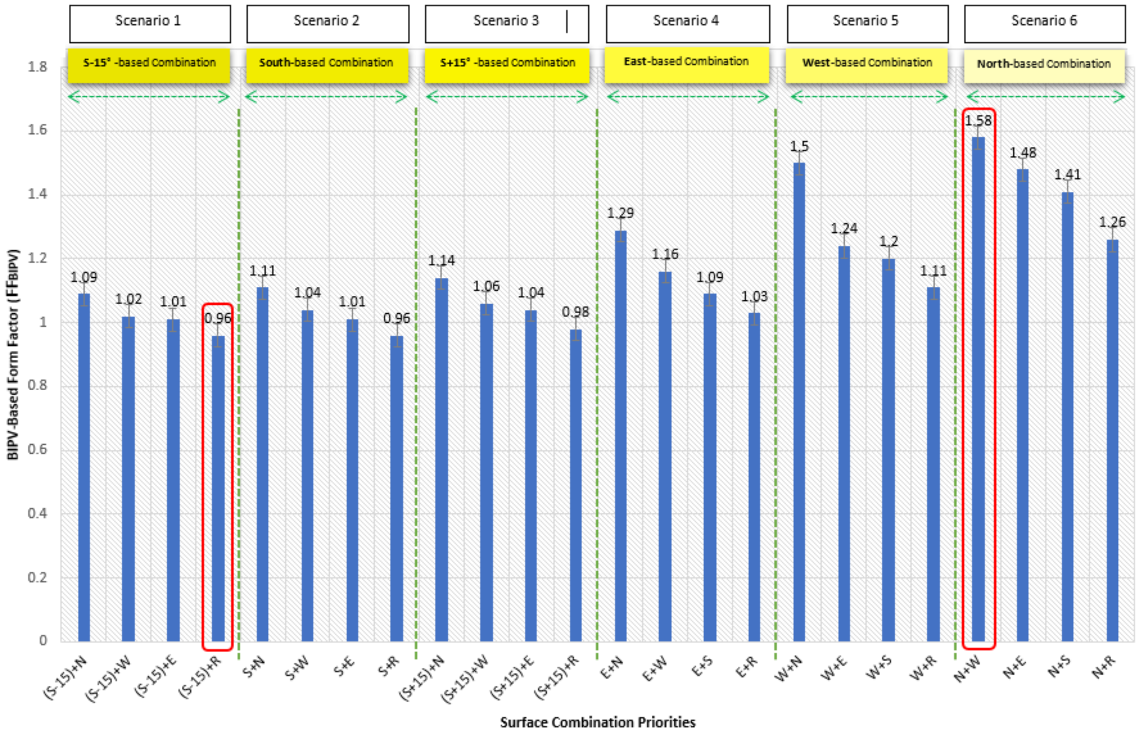


Figure 3.4: BIPV-Based Form Factor (FF_{BIPV}) for the Prototype Model According to the Surface Combination Priorities (Window Areas Excluded) (Author, 2021)

In other words, in Scenario 6, the required surface area on the West façade as P2 is about 80%, compared to 7% of roof area as P2 in Scenario 1. Therefore, the worst choice in this case of Scenario 6 uses 73% more surface area for BIPV coverage for the same energy generation, which is unjustifiable in terms of economic issues and the considerable index for the BIPV efficiency level.

Figure 3.5 shows that, among the different variations in façade combinations, the case of the South-based façade contribution to the roof takes up the least BIPV area; however, the highest BIPV coverage area belongs to the North-based combination with the West façade. The BIPV coverage area difference between these options for Scenario 1 ((S-15°) + R) and Scenario 6 (N+W) is 73%. Therefore, the utilization of the roof surface as a second priority would help lower the BIPV area required to meet the SPED.

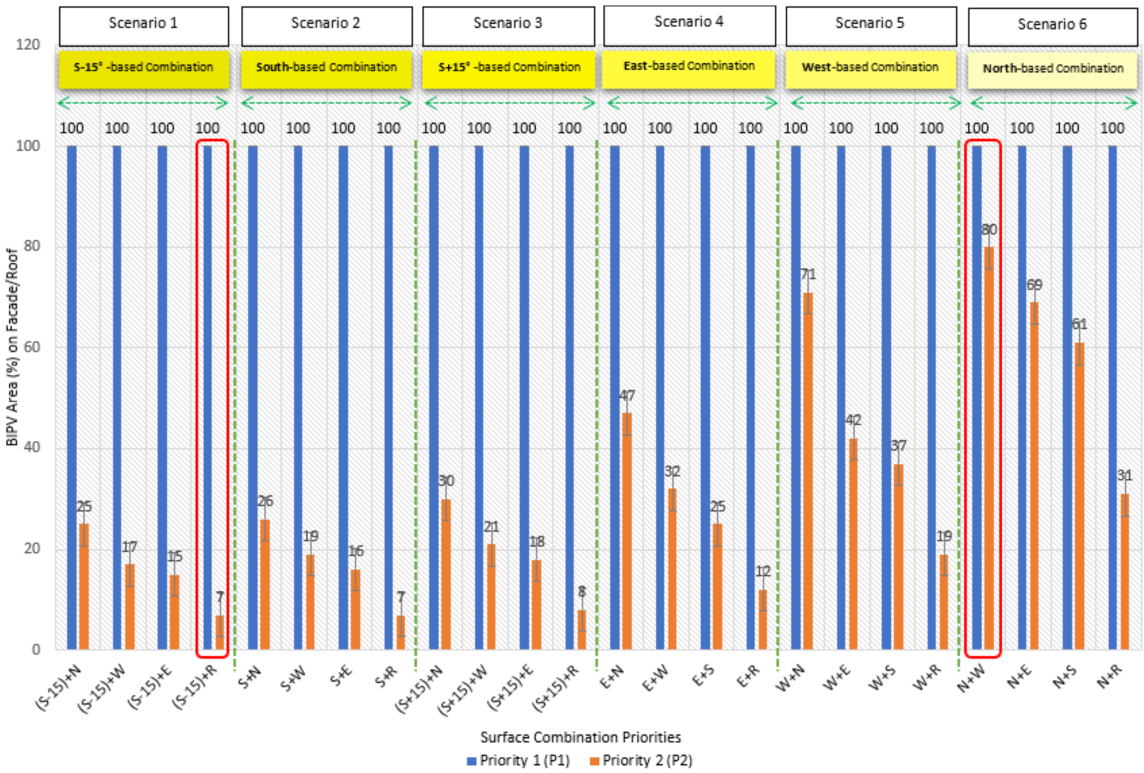


Figure 3.5: BIPV Area Percentage on Façade/Roof for the Prototype Model According to Surface Combination Priorities (Window Areas Excluded) (Author, 2021)

3.3.2 Case Study Analysis Results

3.3.2.1 Building Form Indicators (Form Type Categorizations)

The available twenty-three generated form types with constant volume were categorized into the six groups of A, B, C, D, E, and F according to the A/GFA ratio and the same FF (Figure 3.7). Geographical and physical potential, including building geometry and azimuth, self-shading effect (due to the features of the form types), and global solar radiation for a specific site were investigated to determine the BIPV potential for energy production (SY_{BIPV}) on the thermal envelope of each form type in the six azimuths of N, S, E, W, S±15°. In addition, enough distance for the detached forms was applied to avoid the shading effect. Optimal form type selection for each group was carried out based on the BIPV solar yield (SY_{BIPV}) results in the six azimuths of N, S, E, W, S±15° using the DesignBuilder simulation program (Figurs 3.6, 3.7).

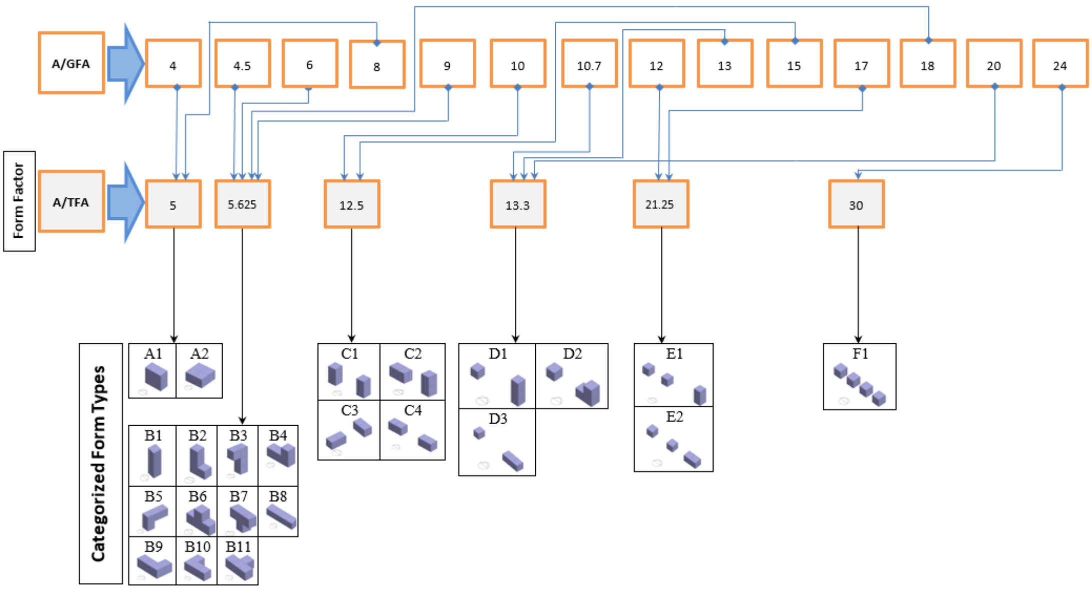


Figure 3.6: Categorized Form Types According to the FF as a Case study (Author, 2021)

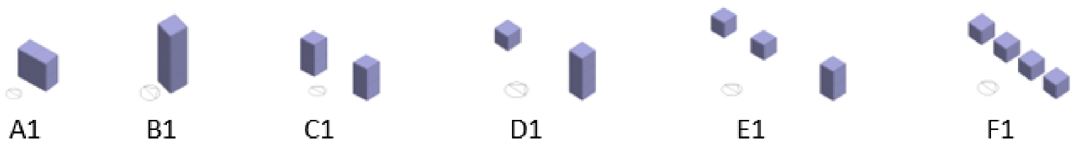


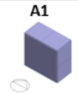
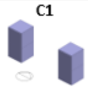
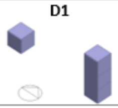
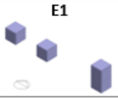
Figure 3.7: Selection of the Optimum Form Types (Author, 2021)

In the following exercise, the UF_{BIPV}, required PV area, CI_{BIPV}, and FF_{BIPV} scenarios for optimal azimuth based on façade and roof combination priorities for the PHS are achieved.

3.3.2.2. BIPV Solar Yield (SY_{BIPV})

The SY_{BIPV} evaluation for the selected form types (A1, B1, C1, D1, E1, and F1) both on roofs and façades determines the BIPV potential for these surfaces, which is simulated using the DesignBuilder program in the six azimuths (Table 3.4). The results represent the maximum solar yield of 3057 kWh for the South façade surfaces, while the azimuth is 165° (South-15°), and windows are excluded (WWR=0.3).

Table 3.4: BIPV Solar yield (SY_{BIPV}) in kWh on Roof and Façades for Selected Form Types in Different Azimuths (Window Areas are Excluded, WWR=0.3) (Author, 2021)

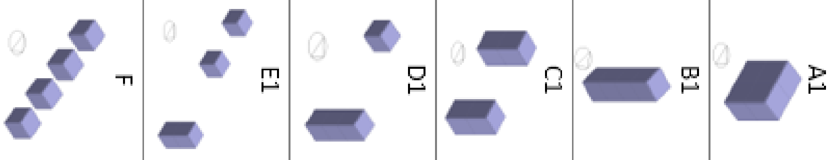
		North				East				South -15°				South				South +15°				West				Azimuth
Selected Form Types	Roof	North	East	South	West	North	East	South	West	North	East	South	West	North	East	South	West	North	East	South	West	North	East	South	West	Surface
A1 	3015	1574	1353	3017	1250	787	2707	1509	2499	1609	1245	3057	1331	1574	1353	3017	1250	1640	1441	2981	1154	787	2707	1509	2499	
B1 	1507	1574	2707	3017	2499	1574	2707	3017	2499	1609	2490	3057	2663	1574	2707	3017	2499	1640	2883	2981	2309	1574	2707	3017	2499	
C1 	3015	1574	2707	3017	2499	1574	2707	3017	2499	1609	2490	3057	2663	1574	2707	3017	2499	1640	2883	2981	2309	1574	2707	3017	2499	
D1 	3015	1574	2707	3017	2499	1574	2707	3017	2499	1609	2490	3057	2663	1574	2707	3017	2499	1640	2883	2981	2309	1574	2707	3017	2499	
E1 	4522	1574	2707	3017	2499	1574	2707	3017	2499	1609	2490	3057	2663	1574	2707	3017	2499	1640	2883	2981	2309	1574	2707	3017	2499	
F1 	6029	1574	2707	3017	2499	1574	2707	3017	2499	1609	2490	3057	2663	1574	2707	3017	2499	1640	2883	2981	2309	1574	2707	3017	2499	

3.3.2.3 BIPV Utilization Factor of Roof ($UF_{BIPV (R)}$)

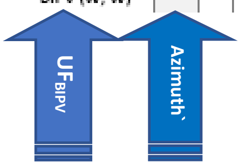
The UF_{BIPV} of the six selected form types were calculated for their roofs and façades in the six azimuths (Table 3.5). The value of the factor for roof ($UF_{BIPV (R)}$) for A1, B1, C1, and D1 form types is less than 1.00, which indicates the insufficiency of the SY_{BIPV} to cover the SPED requirements for the TFA based on the PHS; however, in terms of combination with the partial surfaces of other façades, this standard could be achieved. The E1 and F1 form types have more BIPV solar yield on the roof than the relevant SPED for the total TFA (Table 3.5). In other words, the $UF_{BIPV(R)}$ values for the E1 and F1 form types, 1.31 and 1.74, respectively, are more than the SPED requirements, without any need to combine with other façades (Table 3.5, Figure 3.8).

Furthermore, two best priorities of roof and South façade are used in combination in two scenarios to determine the optimal envelopes for PV integration based on the BIPV coverage index (see Subsection 3.3.3).

Table 3.5: BIPV Utilization Factor for the Selected Form Types in Six Azimuths (WWR=0.3, Roof: $UF_{BIPV\ (R)}$, Façades: $UF_{BIPV\ (Façade,\ Azimuth)}$) (Author, 2021)



Azimuth	Form Type & Shape	A1	B1	C1	D1	E1	F
	Ref. Form Factor	5	5.625	12.5	13.3	21.25	30
	$UF_{BIPV\ (R)}$	0.87	0.44	0.87	0.87	1.31	1.74
North (0°)	$UF_{BIPV\ (N,\ N)}$	0.46	0.46	0.46	0.46	0.46	0.46
	$UF_{BIPV\ (E,\ N)}$	0.39	0.78	0.78	0.78	0.78	0.78
	$UF_{BIPV\ (S,\ N)}$	0.87	0.87	0.87	0.87	0.87	0.87
	$UF_{BIPV\ (W,\ N)}$	0.36	0.72	0.72	0.72	0.72	0.72
East (90°)	$UF_{BIPV\ (N,\ E)}$	0.23	0.46	0.45	0.45	0.45	0.45
	$UF_{BIPV\ (E,\ E)}$	0.78	0.78	0.78	0.79	0.79	0.79
	$UF_{BIPV\ (S,\ E)}$	0.44	0.86	0.88	0.88	0.88	0.88
	$UF_{BIPV\ (W,\ E)}$	0.72	0.72	0.72	0.72	0.72	0.72
South-15° (165°)	$UF_{BIPV\ (N,\ 165)}$	0.47	0.47	0.47	0.47	0.47	0.47
	$UF_{BIPV\ (E,\ 165)}$	0.36	0.72	0.72	0.72	0.72	0.72
	$UF_{BIPV\ (S,\ 165)}$	0.89	0.89	0.89	0.89	0.89	0.89
	$UF_{BIPV\ (W,\ 165)}$	0.39	0.78	0.78	0.78	0.78	0.78
South (180°)	$UF_{BIPV\ (N,\ S)}$	0.46	0.46	0.72	0.46	0.46	0.46
	$UF_{BIPV\ (E,\ S)}$	0.39	0.78	0.78	0.78	0.78	0.78
	$UF_{BIPV\ (S,\ S)}$	0.87	0.87	0.87	0.87	0.87	0.87
	$UF_{BIPV\ (W,\ S)}$	0.36	0.72	0.72	0.72	0.72	0.72
South +15° (195°)	$UF_{BIPV\ (N,\ 195)}$	0.48	0.48	0.48	0.48	0.48	0.48
	$UF_{BIPV\ (E,\ 195)}$	0.42	0.83	0.83	0.83	0.83	0.83
	$UF_{BIPV\ (S,\ 195)}$	0.86	0.86	0.86	0.86	0.86	0.86
	$UF_{BIPV\ (W,\ 195)}$	0.33	0.67	0.67	0.67	0.67	0.67
West (270°)	$UF_{BIPV\ (N,\ W)}$	0.23	0.46	0.45	0.45	0.45	0.45
	$UF_{BIPV\ (E,\ W)}$	0.78	0.78	0.78	0.79	0.79	0.79
	$UF_{BIPV\ (S,\ W)}$	0.44	0.87	0.88	0.88	0.88	0.88
	$UF_{BIPV\ (W,\ W)}$	0.72	0.72	0.72	0.72	0.72	0.72



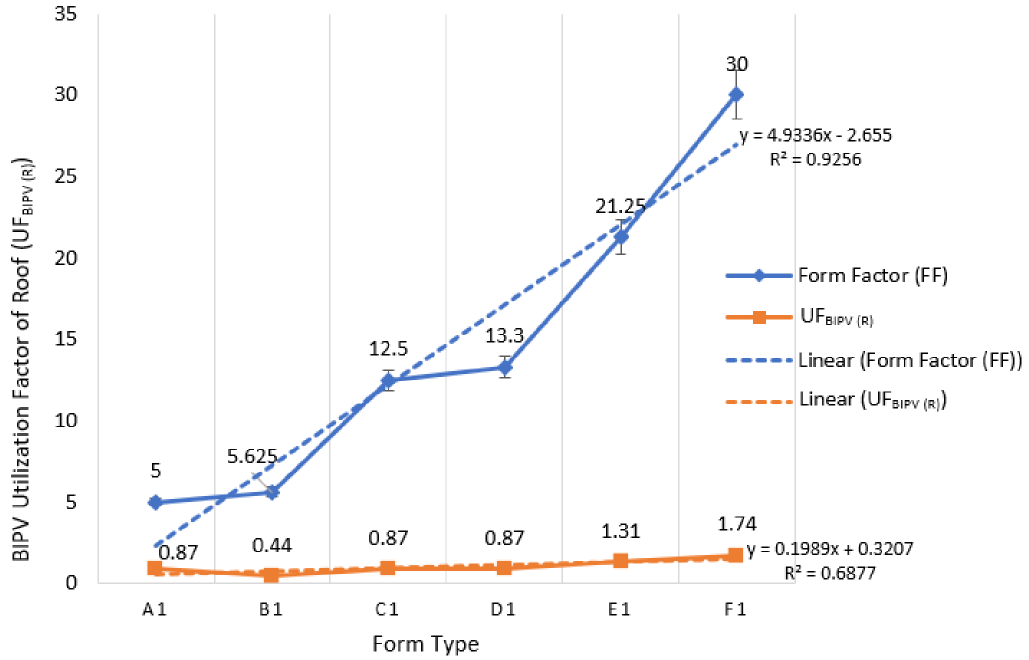


Figure 3.8: BIPV Utilization Factor of Roof Surfaces ($UF_{BIPV\ (R)}$) for the Selected Form Types (Author, 2021)

3.3.2.4 BIPV Utilization Factor of North Façade ($UF_{BIPV\ (N)}$)

For all the form types with the directions mentioned above, except the East and West azimuths for type A1, the ratio of SY_{BIPV} to SPED (UF_{BIPV}) falls in the range 46%–48% when the monocrystalline silicon (mono c-Si) technology for PV is applied. Therefore, there is an electricity generation gap in the range 52%–54% to meet the SPED. On the other hand, the North wall has the least solar yield of all the façades. Consequently, utilization of thin-film technologies, such as amorphous thin-film silicon (a-Si), which has a lower cost but half the efficiency compared to the mono c-Si, is recommended. Additionally, a-Si is beneficial at high ambient temperatures, which makes it a suitable choice in hot, dry climates (Figure 3.9).

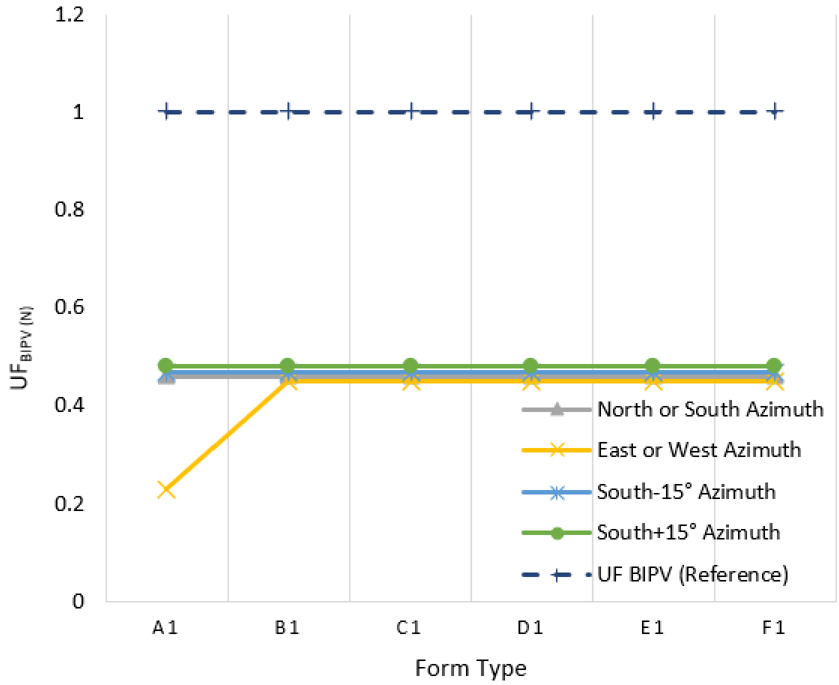


Figure 3.9: BIPV Utilization Factor of North Façade ($UF_{BIPV\ (N)}$) in Different Azimuths (Author, 2021)

If PV is based on mono c-Si technology, the UF_{BIPV} for the North façade (WWR=0.3) for the six selected form types and related six azimuths is limited between 0.46 and 0.48, except for the East and West azimuths for the A1 type, which is only 0.23.

3.3.2.5 BIPV Utilization Factor of East Façade ($UF_{BIPV\ (E)}$)

For the East façade, the UF $_{BIPV(E)}$ ratio of BIPV solar yield to SPED for all directions and form types, except the North, South, South-15°, and South+15° for form type A1, falls in the range 72%–83% when mono c-Si is used. In other words, there is an electricity generation gap in the range 17%–28% to meet the SPED requirements, which may be stored in a PV solar battery or fed into the grid. If PV is based on the mono c-Si technology, the $UF_{BIPV(E)}$ for all directions for the form types B1, C1, D1, E1, and F1 lies between 0.72 and 0.83 (Figure 3.10).

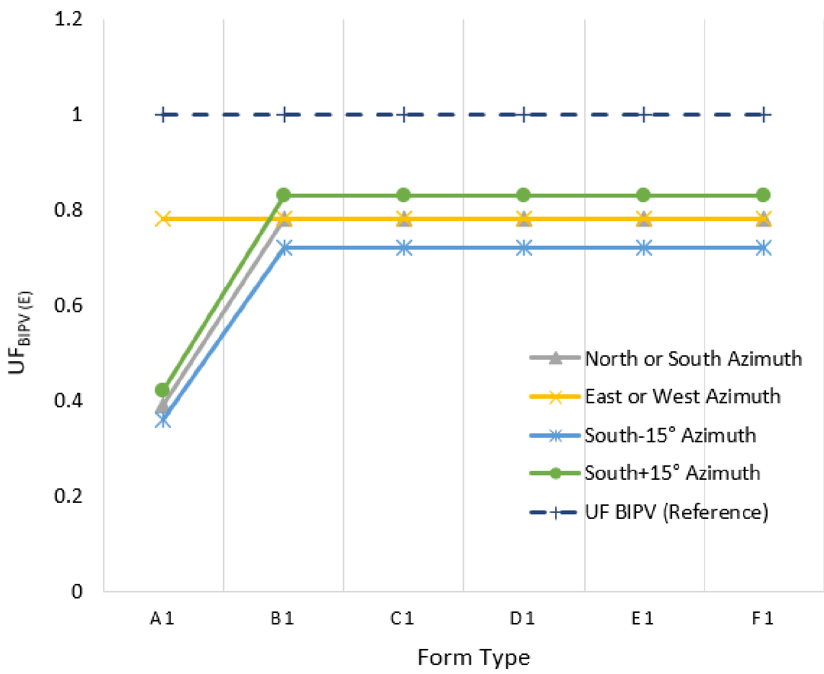


Figure 3.10: BIPV Utilization Factor for the East Façade ($UF_{BIPV\ (E)}$) in Different Azimuths (Author, 2021)

Additionally, the $UF_{BIPV\ (E,\ E)}$ and $UF_{BIPV\ (E,\ W)}$ values for the A1 form type are similar to those for the five previous form types, B1 to F1; however, the BIPV utilization factor for the remaining azimuths of the East façade varies in the range 0.36–0.42. Moreover, for this case, the $UF_{BIPV\ (E,195°)}$ for all forms, except A1, would be the best configuration with only a fraction, 0.17, relative to the reference value, required to meet the SPED requirements.

3.3.2.6 BIPV Utilization Factor of South Façade ($UF_{BIPV\ (S)}$)

Based on different azimuths, PV integration in the South façade of each form type generates solar electricity in the range 86%–89% to meet the SPED. If PV is based on mono c-Si technology, the $UF_{BIPV\ (S)}$ for all forms is limited to the range 0.86–0.89, except for the A1 form, with a value of 0.44 for the azimuth of 165° (Figure 3.11).

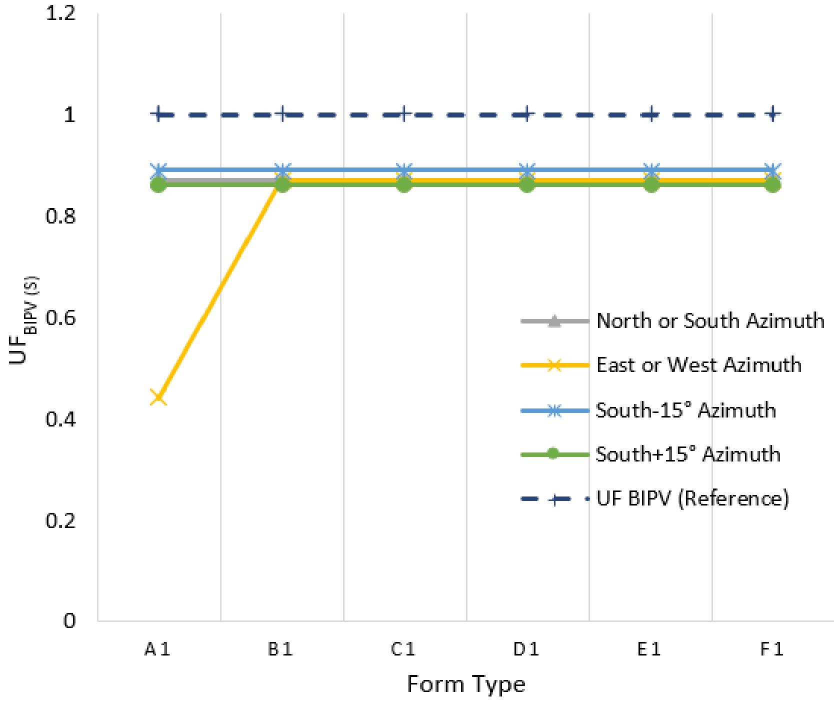


Figure 3.11: BIPV Utilization Factor for the South Façade ($UF_{BIPV\ (S)}$) in Different Azimuths (Author, 2021)

3.3.2.7 BIPV Utilization Factor for the West Façade ($UF_{BIPV\ (W)}$)

All form types, except A1, produce 72% of the solar electricity required to meet the SPED for the azimuths of North/South, East/West, and South-15°. However, this ratio falls to 67% for the South+15° azimuth to fully cover the SPED. Meanwhile, the treatment of the selected form types for energy generation varies in the range 33%–78%. However, its minimum ratio of 33% is for the South+15° direction, while the maximum one refers to the South-15° azimuth. Consequently, assuming a WWR of 0.3, no PV integration option in the walls would cover the SPED by itself. Hence, assistance from other surfaces would be required (Figure 3.12).

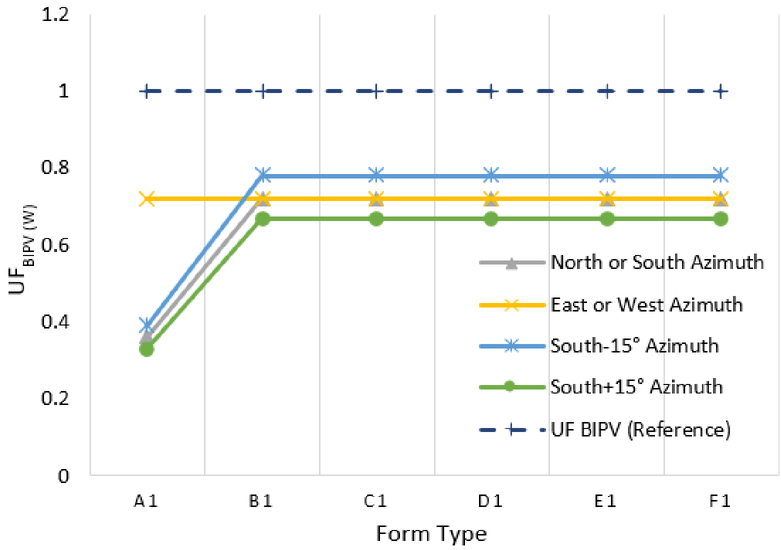


Figure 3.12: BIPV Utilization Factor for the West Façade ($UF_{BIPV\ (W)}$) in Different Azimuths (Author, 2021)

3.3.3 Priorities and Scenarios

As no façade can cover the SPED requirements by itself, façade combinations with each other or with the roof, based on the priorities for the different azimuths, is calculated for the six form types. Two scenarios based on the best priority combinations for the optimal azimuth of 165° (South-15°) (Table 3.6) are defined and used to determine the main factors presented in the following tables and figures.

Table 3.6: BIPV Combination Scenario Based on the Priorities (Author, 2021)

	BIPV Combination Priorities (P1+P2)	
Scenarios	**Priority 1 (P1)**	**Priority 2 (P2)**
Scenario 1 (S+R)	South façade, Azimuth: South-15°	Roof
Scenario 2 (R+S)	Roof	South façade, Azimuth: South-15°

In Scenario 1, due to the total SPED, the opaque part of the South façade (except the window area, which is 30% of the total South façade) is assumed to be covered fully by the BIPV system. However, in Scenario 2, since the $SY_{BIPV(R)}$ is higher than those of the façades by itself, depending on the form type, partial or total roof area is specified for the BIPV coverage to achieve the PHS.

According to Scenario 1 (Table 3.7), the FF_{BIPV}, which employs the South façade as the first priority, is approximately 0.96 for all of the selected form types (Figure 3.13). However, the FF_{BIPV} receives considerable variations (0.71–0.87) in Scenario 2 compared to Scenario 1 (0.96); the correlation (R^2) of the CI_{BIPV} for the South-based façade ($CI_{BIPV(S+R)}$) in Scenario 1, with a value of 0.92, is higher than the roof-based case ($CI_{BIPV(R+S)}$) value in Scenario 2, with a value of 0.84 (Figures 3.13, 3.14). This difference between the R^2 values is due to the distinct CI_{BIPV} treatment of the B1 form type for roof-based combination priorities with the highest value of 0.16 among the selected form types. Despite the difference in the FF_{BIPV} values in Scenarios 1 and 2, the small difference of 0.08 in the linear regression (R^2) between these scenarios demonstrates the high correlation between these six selected form types regarding FF_{BIPV}. On the other hand, a pairwise comparison of the CI_{BIPV} values for each form type obtained in the two scenarios shows that the BIPV utilization in Scenario 1 is 1.13 to 1.35 times that in Scenario 2, which indicates a priority configuration for the surfaces' combination. Similarly, the FF_{BIPV} obtained from the first scenario is 1.1 to 1.35 times that in the second scenario. However, the FF_{BIPV} for the six selected forms in Scenario 1 is equal to that of the prototype form type with a constant value of 0.96, which demonstrates the reliability of the FF_{BIPV} as a helpful tool in determining the relationship between the A and the TFA for BIPV potential (Table 3.7).

Table 3.7: Best Priority Combination for the Selected Form Types (Azimuth=South-15°) (Author, 2021)

		Scenario 1				**Scenario 2**			
		South-based Façade (S) Azimuth: South-15° (Priority 1 + Priority 2)				**Roof-based (R) Azimuth: South-15° (Priority 1 + Priority 2)**			
Form Type	Form Factor (FF)	Priority 1 Area (P1: South Façade) Area	Priority 2 Area (P2: Roof) Area	BIPV Coverage Index (CI_{BIPV}) = $A_{BIPV\ (P1+P2)}$ / $A_{Envelope}$	BIPV-based Form Factor (FF_{BIPV}) = $A_{BIPV\ (P1+P2)}$ /TFA	Priority 1 Area (P1: Roof) Area	Priority 2 Area (P2: South Façade) Area	BIPV Coverage Index (CI_{BIPV}) = $A_{BIPV\ (P1+P2)}$ / $A_{Envelope}$	BIPV-based Form Factor (FF_{BIPV}) = $A_{BIPV\ (P1+P2)}$ /TFA
A1	5	South 100%	Roof 13%	0.19	0.96	Roof 100%	South 14%	0.15	0.75
B1	5.625	South 100%	Roof 27%	0.17	0.96	Roof 100%	South 64%	0.16	0.87
C1	12.5	South 100%	Roof 13%	0.15	0.96	Roof 100%	South 14%	0.12	0.75
D1	13.3	South 100%	Roof 13%	0.15	0.96	Roof 100%	South 14%	0.12	0.75
E1	21.25	South 100%	Roof 9%	0.14	0.96	Roof 68%	South 0%	0.10	0.71
F1	30	South 100%	Roof 7%	0.13	0.96	Roof 57%	South 0%	0.10	0.71

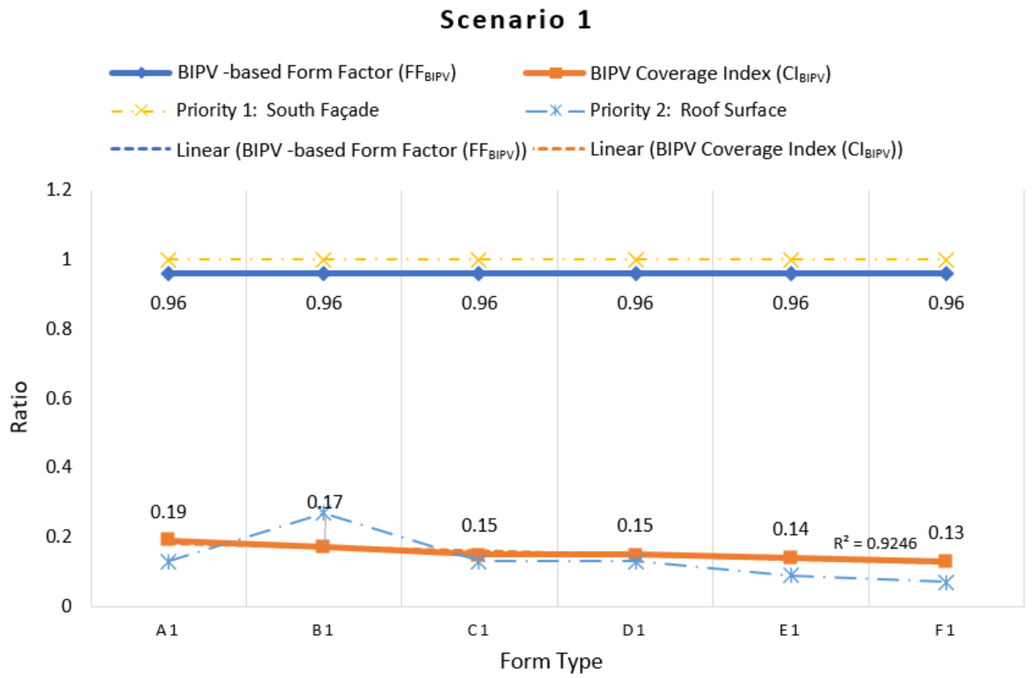


Figure 3.13: BIPV-Based Form Factor and BIPV Coverage Index in Scenario 1 Based on Surface Combination Priorities (Priority 1: South Façade, Priority 2: Roof Surface) (Author, 2021)

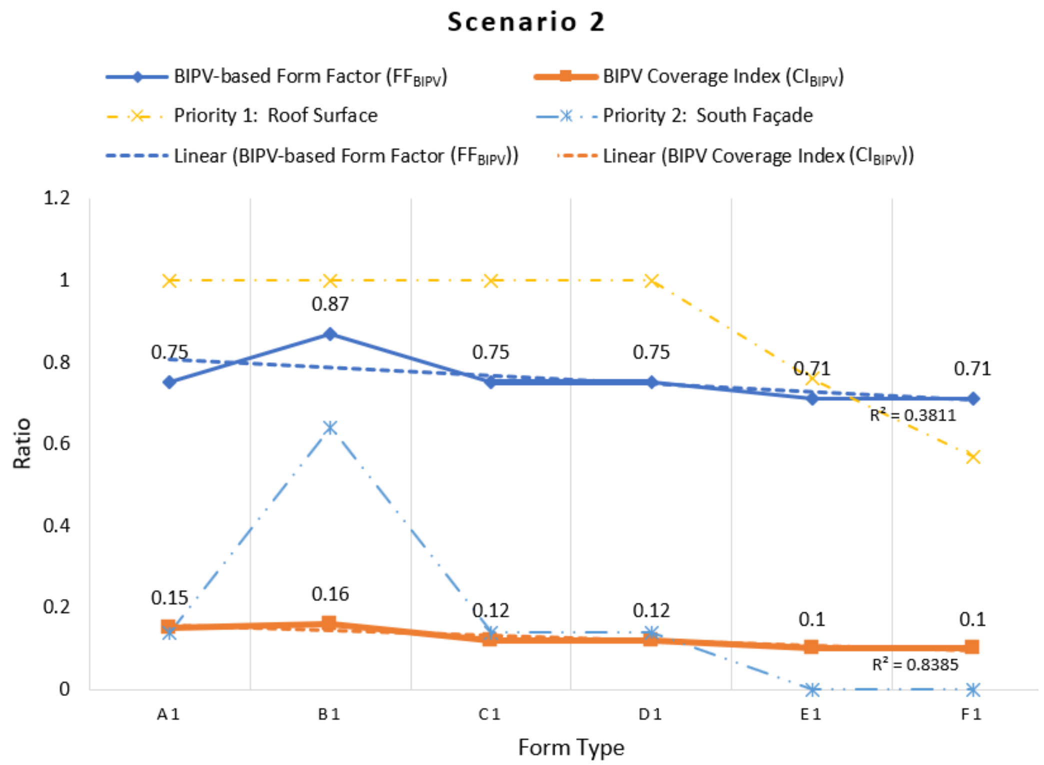


Figure 3.14: BIPV-Based Form Factor and BIPV Coverage Index in Scenario 2 Based on Surface Combination Priorities (Priority 1: Roof Surface, Priority 2: South Façade) (Author, 2021)

Although the minimum effect of surfaces' priorities for combination regarding the BIPV coverage index (CI_{BIPV}) is from the B1 form with the minimum roof surface area, Scenario 2 still utilizes 21% less BIPV area than Scenario 1. Possibly due to the high solar yield on the roof surface, the roof-based CI_{BIPV} utilizes less BIPV area and is considered more economical compared to the South-based ones. In both Scenario 1 and 2, form B1 receives the highest BIPV coverage percentage of 27% and 64%, respectively, due to the small roof surfaces among the other forms related to the thermal envelope (Table 3.7) (Figure 3.13 and 3.14).

3.4 Validation of Results

According to the results of the simulation of the prototype form for surface combination priorities, ((S-15°)+R) in Scenario 1, with a value of 0.96, has the lowest FF_{BIPV} of the six scenarios. In other words, it is shown that the S-15°-based combination is the best priority combination to achieve the lowest value for the FF_{BIPV} (Figure 3.5).

Additionally, regarding the selected form types in the case study (A1, B1, C1, D1, E1, and F1), the calculation results in Scenario 1 ((S-15°+R)) (Table 3.7) show the same value of 0.96 for the FF_{BIPV}, which validates the results. However, in Scenario 2 (Table3.7), which is a roof-based combination, different values for FF_{BIPV}, in the range 0.71 to 0.87, are observed. These values differ by, at least, 0.09, and, at most, by 0.25 from the 0.96 in Scenario 1. Therefore, Scenario 1, and not Scenario 2, qualifies for use in the validation of the results.

Chapter 4

CONCLUSION

BIPV is a promising, multi-functional, active solar technology that offers cleaner energy production for energy efficiency and added value to buildings. Hence, PV integration into the building envelope plays a prominent role in building shape formation and its geometric factors. Smart and logical application of BIPV in appropriate positions in roofs and façades would be a significant and straightforward step to achieving net-zero energy buildings.

This research investigated the efficiency of the BIPV by developing a parametric methodology to establish the relation and correlation between, on the one hand, the active envelope area potential for electricity generation that is required to cover the SPED, and, on the other, the TFA, based on the PHS.

C (A/V ratio) implies 3-D volume efficiency, whereas FF predicates the architectural performance of the enclosure surfaces in correlation with the functional floor areas for better results. Hence, architects and decision-makers in the building sector are interested in the energy demand per square meter of TFA. Understanding the relationship between the generated energy by the BIPV area on the enclosure and TFA for given forms provides advantages for energy management in the preliminary steps of the design process. For this purpose, FF is employed and developed as a BIPV-based FF (FF_{BIPV}) to identify the BIPV location and area for optimal combination priorities of façade and roof surfaces. So, FF_{BIPV} determines the building energy demand and generated solar energy on the envelopes. However, first, optimal form selection is carried out by evaluating different form configurations based on the same FF and BIPV utilization factor. Thereafter, the BIPV efficiency level is examined through its utilization factor and coverage index scenarios based on façade and roof combination priorities. Optimal form determination is then carried out by analyzing the available PV area ratio on the exposed surfaces to the TFA for a determination of the utilized BIPV energy efficiency level. The resulting high correlation value (R^2) of 0.92 and 0.84 in both scenarios for the BIPV coverage index related to the total envelope indicates its accuracy, high reliability of TFA and FF tools, validation due to its high R^2 value for the optimal forms and azimuths, and can be extended and developed for other forms in different locations.

Although the roof-based scenario obtains less BIPV area usage (CI_{BIPV} in the range 0.10 to 0.13), equivalent to a high BIPV utilization factor and a better economic viability in comparison to the South-based scenario (CI_{BIPV} in the range 0.13 to 0.19), the South-based façade combination scenario maintains the FF_{BIPV} at 0.96 with utmost accuracy, neutralizing the effect of form type differences and thus helping to determine the optimal building envelope.

Beyond the above discussions, the climate type in any location has its effect on the formation and the ratio of openings and the elongation or compression of the building, but ultimately the CI_{BIPV} and also FF_{BIPV} is related to the optimal combination of available surface areas on roof and facades.

In conventional compact form buildings located in the middle latitude of the Northern hemisphere in cold climates, combining the southern facade area with the roof area would be the best scenario to meet SPED requirements, CI_{BIPV}, and FF_{BIPV} based on PHS. However, the buildings located in humid climates, which have more elongation in the building form to make maximum use of natural ventilation, combining the South façade with roof or East/West façade must be done in coordination with ventilation priority.

At high latitudes in Northern hemisphere (e.g., Canada and Scandinavian countries), the angle of solar radiation and consequently the solar yield is low, therefore, for PV integration, building facades are more important than roofs. In other words, for the prototype form in this location, combination of South façade as the first priority with second priority of East or West façade would be the best scenario to achieve the optimum FF_{BIPV} and CI_{BIPV} with high R^2 value. But, for the building located in high latitudes in Southern hemisphere everything is the same except changing the first priority to North façade. However, for different form types depending on the East/West surface areas, FF_{BIPV} and CI_{BIPV} can be varied but they must be investigated in deep research to find out the clear results by the robust method.

Furthermore, the compact high-rise buildings take advantages of more exposed surface areas on facades comparing the roof area, have more flexibility than linear ones for PV integration within highly acceptable UF_{BIPV}, CI_{BIPV} and FF_{BIPV}.

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