Department of Materials and Environmental Technology

DEVELOPMENT OF COLOURED BIPV SYSTEMS ON METAL ROOFS

VÄRVILISTE EHITISINTEGREERITUD PÄIKESEPANEELIDE ARENDUS METALLKATUSTELE

MASTER THESIS

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AUTHOR’S DECLARATION

Hereby I declare, that I have written this thesis independently.

No academic degree has been applied for based on this material. All works, major viewpoints and data of the other authors used in this thesis have been referenced.

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THESIS TASK

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Study programme: Materials and Processes for Sustainable Energetics,

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Thesis topic: Development of Coloured BIPV Systems on Metal Roofs

(Estonian) Värviliste Ehitisintegreeritud Päikesepaneelide Arendus Metallkatustele

Thesis main objectives:

1. Developing possible solutions for coloured PV module design that can be mounted on metal roofs.
2. Evaluating different types of material for each possible coloured PV module and assessing each designed module according to their technical capability and visual appearance.
3. Benchmarking coloured PV modules for their economic feasibility, visual aesthetics, technical viability, and their applicability for commercial scale production.

Thesis tasks and time schedule:

No	Task description	Deadline
1.	Collecting background information and surveying to find optimum materials. Collecting information for collaborations with companies for material order.	16.04.2018
2.	Contacting companies for material orders and pre-test evaluations	16.04.2018
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ABSTRACT:

Due to increased customer desire and interest, environmental and local restrictions, increased technical availability, and PV market extension that was led by dropped material prices; BIPV systems secure its position in PV industry and new innovative designs for more aesthetic options has become essential. BIPV system implementation in a commercial scale requires optimisation for economic feasibility and technical capability while offering visually aesthetic design. Therefore, different coloured PV systems gain huge importance and optimising visual and technical characteristics needs to be investigated. In this thesis, EVA encapsulated foil, multi-crystalline solar cell, special Solaxess, intermediate encapsulant foil, digitally ceramic printing, and multi-layer interference optic filter are investigated in different colours and possible implementation on metal rooftops for commercial scale manufacturing. Visual appearance for each laminated PV module is completed by matching them with the same coloured metal backsheets, AutoCAD designs are rendered for visual simulations. Economic assessments and output power measurements are completed the prices of one module per Watt power is calculated for each manufactured PV module. Reference module is also manufactured by laminating mono-crystalline solar cells for nominal output power comparison and gives the lowest value by having 0.66 €/Wp. Second lowest values is achieved from PV modules that are laminated by coloured EVA encapsulating foils and they have an average of 1.21 €/Wp, followed by PV modules that are laminated with coloured multi-crystalline solar cells which costs an average of 1.41 €/Wp. Module using Solaxess foil has one of the highest costs by having 2.25 €/Wp. Modules that is laminated by digitally ceramic printed front glass gives high cost per watt values; having 2.18 €/Wp, for red, 2.64 €/Wp is for blue, 2.5 €/Wp for green, and 2.4 €/Wp for grey coloured front glass. 84 % coverage has visually the best appearance.

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PREFACE:

The research has been done in collaboration with the private company Roofit.solar and this work is financed by the company as part of their product development. Firstly, I present my humble gratitude to my supervisor Andri Jagomägi for his professional guidance, his support, advices and time to make this research possible. I also convey my thanks to Iryna Yakobiuk as an employee of Roofit.solar for her help and efforts, to Solaxess SA., Glas Trösch Holding AG., LOF Solar Corp., Luoyang Lever Industry Corp., and every other private company for their collaboration to make this project feasible. Finally, I would like to express my deep appreciation to my family for their endless support.

This research represents a benchmark for possible material applications for coloured BIPV systems design on metal roofs and their visual and economic analysis on a commercial scale production.

Key words: BIPV, coloured PV module, coloured BIPV.

NOMENCLATURE:

FF -Fill factor

G- Irradiation [W/m^2]

Impp- Maximum Power Current [A]

Isc- Short circuit current [A]

Pmax-Maximum Power [W]

Vmpp- Maximum Power Voltage [V]

Voc- Open circuit voltage [V]

Wp- Watt Power

ABBREVIATIONS:

BAPV: Building Applied Photovoltaic

BB: Busbar

BIPV: Building Integrated Photovoltaic

CdTe: Cadmium Telluride

CIGS: Copper Indium Gallium Diselenide

CZTS: Copper Zinc Tin Sulphide

EVA: Ethylene Vinyl Acetate

LCOE: Levelised Cost of Electricity

PET: Polyethylene terephthalate

POE: Polyolefin

PV: Photovoltaic

PVB: Polyvinyl Butyral

STC: Standard Test Conditions

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1. INTRODUCTION:

Buildings are immense energy consumers that need it for various applications and usually, this energy is provided in polluted and complex systems. PV integration for energy supply would both reduce using these external energies and increase the multi-functionality of a building itself by making it part of an urban ecosystem [1].

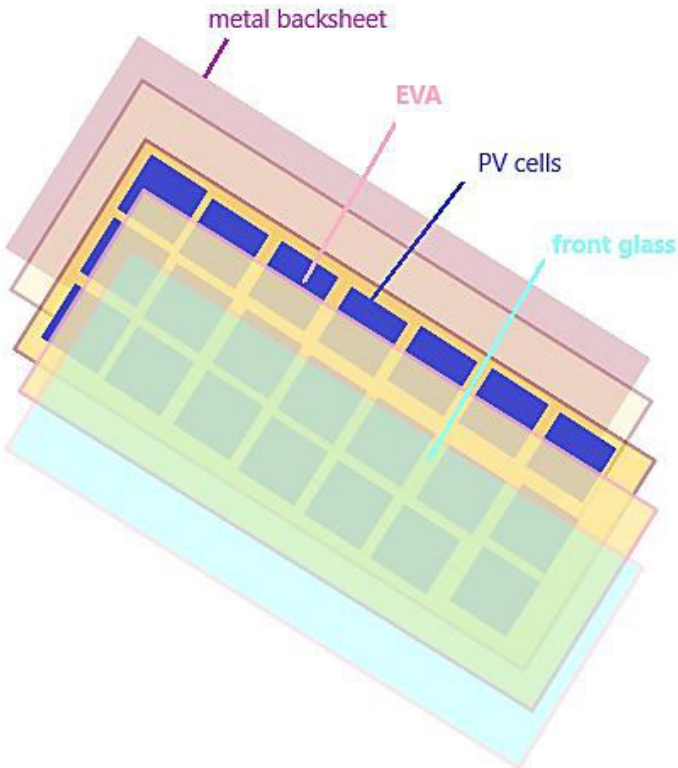
Residential PV is highly influenced by consumer perception; hence, it is still considered as an early adaptive technology by users, even though residential PV has been developed by experts since the 80s. Future strategies from United Nations Framework Convention on Climate Change (UNFCCC) and European Commission ramped up the use of renewable energies as well with solar energy industry. More companies have been involving in this new energy race with their unique design and material selection.

Due to customer desire, restrictions of historical buildings, and BIPV technology developments led engineers and architects working on visual changes of solar PV modules altogether. Natural integration of PV systems should be completed by fusing and optimising PV systems with good material, colour composition, and adapt these systems in the context of the building design; innovate a solution for buildings to generate clean energy while still having a satisfactory visual look. When aesthetic design came later than technical optimisation, PV modules were looking rather dark and visually unsatisfied. Market extension lowered the prices for conventional PV module materials; meanwhile the customer centred designs are becoming more popular. Previous studies show that house owners desire to put solar panels that have the same colour as their rooftops rather than putting conventional PV modules that have dark colour. BIPV integration on façades has more possibilities in terms of architectural integrity; however, the technology needs some developments to improve visual aspect such as transparency, colour, and other system design configurations.

Technology advances provides BIPV systems to mount on not only conventional concrete or tiled roofs but also metal roofing. In fact, due to energy efficient characteristics of light coloured metal roofing materials that also are more durable and highly resistant for harsh environmental conditions, causes the demand for metal roofing in commercial building constructions increase. With this increased demand for metal roofing, innovative design modifications for BIPV implementation on metal roofing also become more important. Moreover, economic feasibility of commercial applications of manufacturing BIPV systems that implemented on metal roofs has a crucial importance.

2. OBJECTIVES OF THE STUDY:

In attempting to investigate factors which account for optimisation for BIPV systems integrated on metal roofs as it was briefly mentioned in Introduction section, this thesis constructs series of experiments for benchmarking both visual appearances and commercial feasibility of PV modules that are laminated with materials as stated below;



- coloured PV multi-crystalline cells,
- coloured EVA encapsulants,
- multilayer interference filter,
- additional special encapsulant foil,
- digitally ceramic printed front glass,

Figure 1. Schematic representation of the objectives of the thesis.

All cases are assessed under the same lamination parameters and same lamination process with associated elements for BIPV photovoltaic module with the size of 54x136 cm and three parallel lines that consists of eight cells connected to each other. Adhesion of each layer of modules is mediated through POE (polyolefin) layer which is proved to give a better performance than EVA encapsulation [51].

Before power output tests, visual optimisation is made by laminating coloured layers with different metal/polymer backsheet options to merge the modules best for roofing metal colours or by preparing a visual representation using AutoCAD. Best possible visual matches then is laminated to perform as PV module and tested for power efficiency. Each process will be explained in detail in Section 5.

Results of all assessments are considered according to commercial scale for further mass productions; hence economical results of the materials was as equally important as both visual appearance and technical output of the processed modules. Economical evaluations and technical characteristics of each module will be presented in Section 6.

3. LITERATURE REVIEW:

3.1. Background:

Climate change, increase of atmospheric greenhouse gases and number of endangered species led people to look for more environmental options. Harvesting sun to produce energy has naturally become one of the best possibilities for greener future. From photovoltaic cells that have been made to power satellites in 1960s to commercial usage in 1970s PV technology has come long way [6]. According to 2017 statistics, PV energy grew faster than any other renewable energy option [2].

More PV capacity was installed in 2016 than past five years instalment combined, which means that more than 31 000 PV modules were installed every hour [3]. China has taken the lead in both manufacture and use of photovoltaics, causing the expansion in the market. In 2016, China covered 77 GW solar PV capacity in total of 291 GW world's capacity and in 2015, China reached estimated 39 GWh total productions of 243 GWh total productions in the world. China's rapid developments on solar energy are also becoming the expediter to other countries [4]. Only in 2016 alone, Europe made a big stride for installing 100 GW off - grid PV, which is considered a new era by energy analysts [5]. Later in 2017, European countries installed at least 8.61 GW of solar power, meaning 28% increase from the last year [7]. Globally, every continent had installed at least 1 GW, meanwhile more than 24 countries had at least 1GW capacity and more than 114 countries had more than 10 MW by the end of 2016. In 2016, Germany, Japan, Italy, Belgium, and Australia had the biggest solar PV capacity in the world [3].

3.2. Solar PV Policies and Market:

PV energy industry booming owe its rising to not only the technology advancements and competitiveness but also to governmental policies in the form of tax subsidies. Governments have started imposing several renewable energy policies to engrain consumers for raising awareness on benefits of using more sustainable energy and consuming less fossil fuel. Furthermore, there are now several local restrictions on new buildings where it is made obligatory to make them more insulated as well as the restrictions on renovations for old buildings to more energy efficient.

Among these social and environmental policies, market-based supports have been ramped up by governments for both customers and investors. Governments subsidies that advocating in the form feed-in tariff or in the form of loans entail the market prices for PV system to down [8], [9]. Feed-in-tariff ensures to pay the price for generating electricity from the PV installed; however, this price varies by each country. Furthermore, Europe and USA started to lower credit on investment taxes and took payback period longer for investment to encourage investors for greener technology [10]. According to IRENA database, PV module prices have declined by 81% during the past nine years as well as the global LCOE with 73% reduction in the same period. Moreover, it is estimating that by 2040 cost for solar PV will drop by 48% [11], [12].

3.3. Scale of PV Systems:

Photovoltaic systems implementation varies in terms of required power output, geographic identifiers, customer needs, and governmental policies. Depending on the operational and functional requirements; PV systems can either supply power directly to an electrical gazette in its stand-alone mode or feed energy into the utility electricity grid in its grid-connected mode [13].

Stand-alone PV systems can be powered by with batteries or by hybrid systems which in this case it is needed to be connected with either a wind turbine, a fuel cell, a diesel generator, or a hydro turbine. Stand-alone systems can be operated in remote areas, in satellites, portable devices as well as in usage of vehicles. Grid-connected PV systems operate in parallel and connected to electric utility grid and as a result they require no storage or batteries. Grid-connected PV systems have huge advantages over stand-alone systems, since they are directly connected to the grid; excess power output can be supplied back to the grid when generated power is greater than the local demand [14],[15]. Their capacities vary from single residential rooftop-mounted PV to large utility scale PV systems that generate electricity like a power plant.

Grid-connected PV systems can be divided into two primary categories as distributed and centralised grid-connected PV systems. Centralised grid-connected PV systems are large scale solar plants that connected to transmission system. These systems are usually mounted on the ground and rural areas. Centralised grid-connected PV systems are generally initiated for specific residential customers.

In contrast to centralised PV systems that act as power plants, distributed grid-connected PV systems are connected to low voltage and medium voltage systems, which make them scalable. This scalability of distributed PV systems allows engineers and module manufacturers to design PV with a size vary from hundreds of watts to hundreds of megawatts [16]. They can be residential, commercial, or industrial systems. Thus, distributed grid-connected PV systems are more common in use than centralised grid-connected PV. Countries where land to excavate, it is very easy to choose roof mounted PV over ground mounted PV. For instance, countries like Germany and Switzerland, almost all PV systems are connected to the distributed systems and their policy support for emphasizing distributed residential PV systems more than ground mounted systems. According to global market outlooks, more than two-thirds of PV systems that whether could be residential, commercial or utility scale are structured as rooftop-mounted systems in Europe (Figure 2).

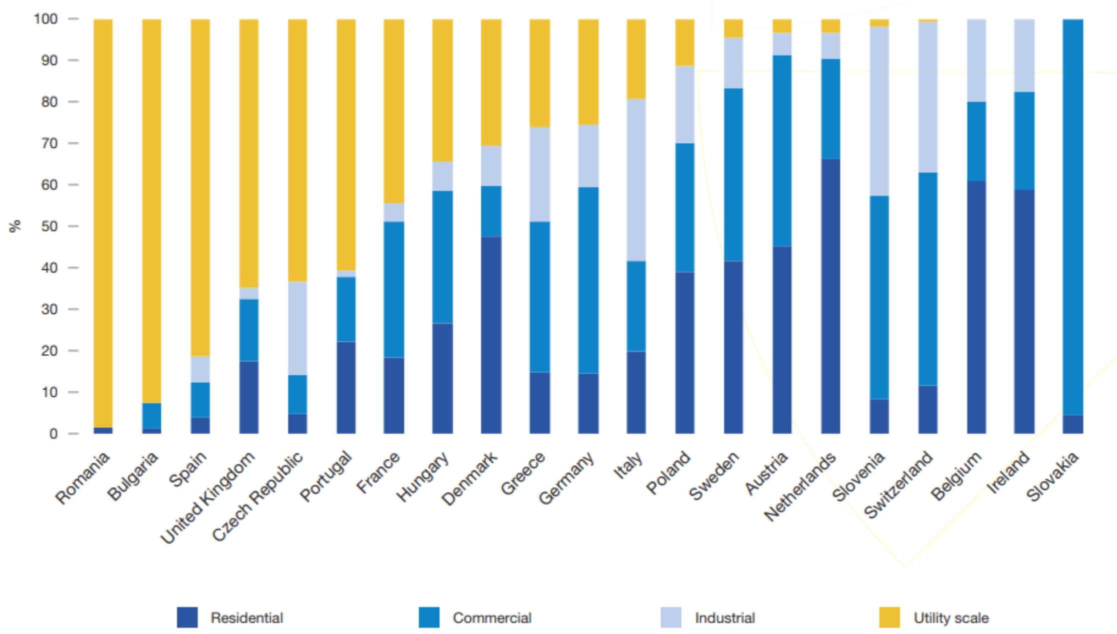


Figure 2. European Solar PV Total Capacity until 2016 for Selected Countries (SolarPower Europe, 2017)

Depending on the function and material/technology preferences, PV systems can also be analysed as building integrated photovoltaic systems (BIPV) and building applied photovoltaic systems (BAPV). BAPV systems are integrated on to rooftop of buildings; only provide electricity for the building they are mounted. BIPV systems on the other hand, have different aspects of not only producing electricity but also act as building element itself [17].

3.4. BIPV Systems:

BIPV systems provide a plethora of opportunity to home owners, architectures, and environmental policy makers to achieve their directives for greener technology. Since European Directive 2010/31/EU obliged building owners and architects to reinforce ‘zero energy conceptualised’ buildings, BIPV systems started to have an enormous popularity [18], [20]. These systems can take over any elements of a building; façade, shading, roof-tiles/shingles, and reflect their characteristics by acting as heat insulation, noise protection, weather protection as well as glazing envelope of a building [17], [18].

As for all photovoltaic systems, BIPV systems output also depend on the amount of sun irradiation that is determined by the location, the inclination, shading rate of the environment and other climate condition as well as technical capabilities of photovoltaics system altogether such as efficiency of the photovoltaics, wiring and electrical networking, and accumulation of dirt, dust on modules [22], [23].

4. OVERVIEW OF BIPV TECHNOLOGY:

Different applications of BIPV define the technology selection for photovoltaic cells. According to Shukla 2016 [20], [21], there are three classifications of BIPV photovoltaics cells:

- first generation which is consistent of mono-crystalline and poly-crystalline (c-Si) PV cells,
- second generation that covers amorphous silicon thin film (a-Si), cadmium-telluride/cadmium-sulphide (CdTe/CdS) and copper-indium-gallium-diselenide (CIGS) PV cells, and
- third generation PV cells consisting of dye-sensitized, copper-zinc-tin-sulphide (CZTS), organic, perovskite, polymer, and quantum dot PV cells. Their characteristics affect the implementation of BIPV system as well as BOS.

First generation solar cells are still the most common in use in BIPV market since they have low production cost and high efficiency. Special material properties of silicon wafer (c-Si) make modules that are manufactured from first generation PV cells more rigid, opaque, and flat than any other technologies. Technically, design requirements such as transparency or homogeneity of a module during lamination with other layers [24]. Mono-crystalline cells are slightly more expensive than poly-crystalline cells [25]. These technologies have a serious drawback; their performance drops significantly when they operate at high temperatures or when partially shading occurs on cells [24]. Each example can be seen in Figure 3.

Amorphous silicon (a-Si) solar cells are the most popular second generation PV cells, having 4-10% lower efficiency than first generation conventional PV cells. Their homogeneity comes with the design feature of amorphous silicon cells, having no boundary for a cell size. Thuwater s amorphous silicon cells aesthetically have more freedom than first generation PV cells. Both a-Si, CIGS, and CdTe have higher temperature durability; their performances are less affected of shading and high temperatures. The module efficiencies of a-Si, CdTe, and CIGS are 6-8%, 9-11%, and 10-12% respectively; entailing more space for the same output that is needed for c-Si PV cells [24], [25]. The representation of cell efficiencies for each type of cell is given in Figure 4.

Third generation PV technology is aimed to increase efficiency of thin film, second generation PV cells. Dye sensitised PV cells can be considered as artificial photosynthesis, which allows this technology to perform really well during cloudy conditions, indirect radiation, even shading occurrences [27]. Both dye sensitised and organic PV cells fall behind the first generation PV cells despite their advantages of having high flexibility, lower production cost due to requiring less silicon, and their ability to adapt more varied lighting conditions [28].

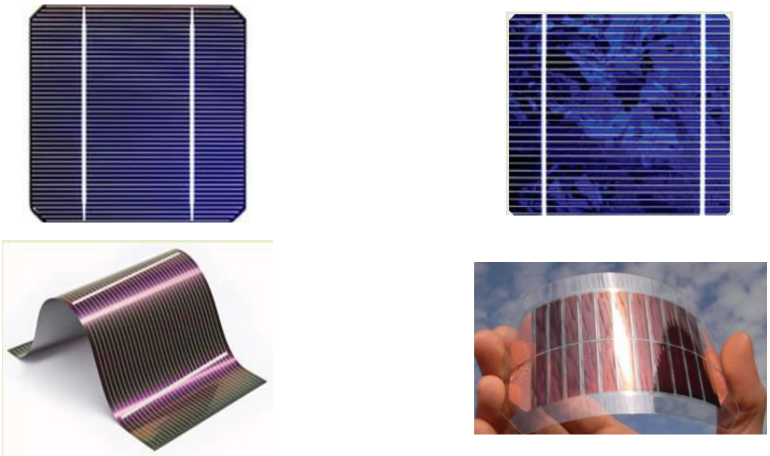


Figure 3. PV cells technologies of mono-crystalline, polycrystalline, thin-film, and dye sensitised PV cells. (Source: http://www.alternative-energy-tutorials.com).

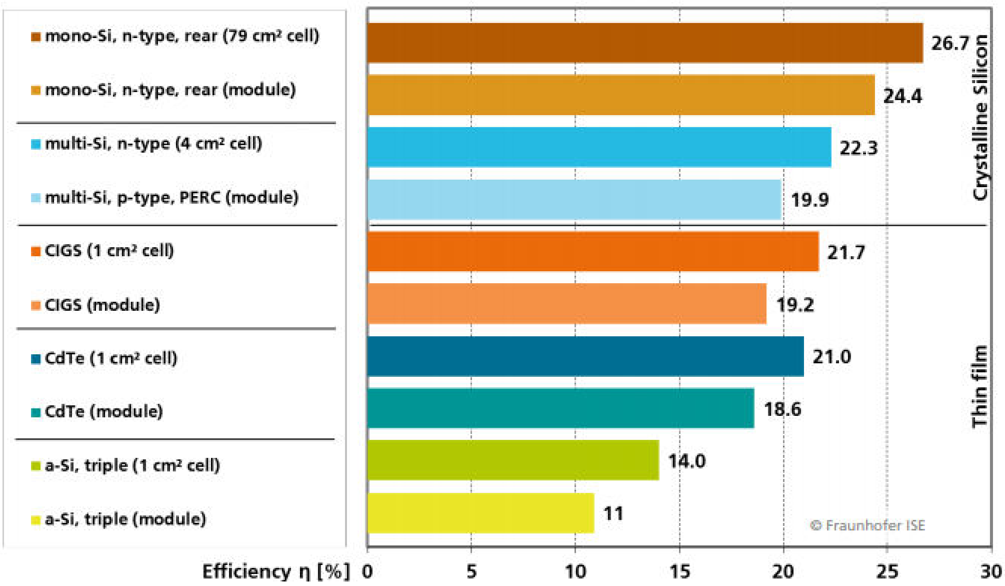


Figure 4. PV cell and module efficiencies of different technologies (Source: Fraunhofer Institute for Solar Energy Systems, ISE, 2018).

Based on the energy output need, material used, their function, design and aesthetical constraints, and technical capabilities BIPV integration,

- can be just on the rooftop of a building, in the form of either a PV module or shingles/tiles,
- can be in small portion by embedding as shading element of a building,

- can be positively unified as a façade system without making inroads on aesthetic codes of architectural design,
- can be fully submerged into a building envelope and change the characteristics of the building overall.

Most common PV cell technology that is used for BIPV is still the first generation PV cells. On the other hand, thin film technology has been commercially used for both roof and façade systems for building integrated building envelopes, whereas dye sensitised solar technology is used for shading and façade areas of the buildings. Translucent effect of thin film PV technology is a relevant factor for using it in BIPV integration in façade systems so that it gives more aesthetical design than conventional PV cells [29], [24].

4.1. BIPV Implementation:

4.1.1. Implementation on Roof:

Being the most conventional method BIPV integration, roofing systems are also sub-divided into categories. Pitched roofs bearing shingles and tiles are known as discontinuous roofs and they are applicable for full-roof mounting systems, solar glazing, in-roof mounting systems, tile systems, and metal panels. Flat or curved roofs on the other hand, known as continuous roof, and their main function is to be water resistant. Since their characteristics are not interrupted by shingle or tile elements, thin film technology can be easily adaptable on such roofs as well as solar glazing, metal panel that are made from conventional PV technologies. One important design choices between c-Si conventional PV cells and thin-film a-Si PV cells is shading elements like chimneys, trees, or towering building surround [24].

Partial roof also known as in-roof mounting systems are used to install first generation PV modules in pitched roof. In this application, module kits are integrated with elements such as frames, clamps to imply conventional PV technology. However, these systems sometimes require roofing layers underneath the modules to prevent water tightness problems. In roof mounting system examples from the world are presented in Figure 5 and 6.

Figure 5. Umweltarena Spreitenbach (Switzerland 2012): an example of a 203% PlusEnergy building achieved by means of a customized 750 kWp full-roof BIPV skin consisting of c-Si panels with an antireflective glass (Architect: René Schmid Architekten; System provider : 3-S Photovoltaics, Meyer & Burger Group; Photo: Bruno Helbling)

Figure 6. Fully covered in-roof installation, Left: (Source: NexPower Technology Corp.) Right: Einfamilienhaus in Glattfelden (Photo: Mirlo Urbano Architekten)

Full integrated or well-integrated BIPV is dully immerged flush mounted system where roof characteristics such as water tightness and mechanical resistance come with the design itself. Unlike in-roof BIPV systems which require extra roofing layer for water tightness, full-roof BIPV systems act as building element ad water tightness is complied with different design possibilities; vertical rails, module overlapping's are developed for such construction requirements [18], [24], [29], [22].

Whether it is fully integrated or partially integrated, BIPV panels can be customised by using light weight material and different lamination techniques. Flexible laminates can be easily applied to pitched flat or curved roofs by pasting onto roofing elements; these systems giving an advantage of these technologies to be a waterproof. Other options for light weight module are laminating PV cells with metal panels where the metal can be selected from different materials such as copper, aluminium, steel etc. or laminating flexible PV panels onto membranes such as thermoplastic polyolefin, polyvinyl chloride etc. [29].

BIPV tile products can be constructed to an entire building or desired part of the roof; they are most suitable systems for historical and traditional buildings where could be restricted to be changed. BIPV tile systems can be designed as large sized (1.60 m) like full-integrated roof or small sized (0.3 m) shingle and slate (Fig. 7). In this case, BIPV solar design is constructed as close as to actual roof tiles of the building. Smaller sized tiles look more aesthetic than larger tiles; however, more time consuming in terms of cabling that is needed to be applied to every single tile. Other disadvantages of these systems are that they are more expensive than conventional methods and the shingles can be easily broken [21], [25], [24], [29].

Figure 7. Left: Vertical tile BIPV solution. System provider: Hemera, Right: Solar shingles. System provider: Solar Century Corp. (Source: P. Heinstein et al., 2017).

4.1.2. Implementation on Façade:

According to A. K. Shukla, 20% of the BIPV market is composed of façade systems, which consists of walls, glazing, cladding as well as other shading accessories and shading elements like balconies, parapets [32]. The design of façade BIPV systems is slightly different than conventional roof-mounted BIPV systems simply because aesthetic value of skin of a building is more important than a rooftop of a building. Configuration of roof-top mounted BIPV lamination can be considered glass-back sheet meanwhile the configuration of façade system BIPV lamination often is glass- glass concerning its visual appearance. This lamination gives the module semi-transparent look; hence, façade systems can be also called as semi-transparent systems. [33], [34]. Some aesthetic designed façade implementation examples are represented in Figure 9.

PV façade systems often require much more complicated planning than conventional PV roof-mounting systems because of the natural characteristics of curtain wall. For instance, a curtain wall works as a thermal insulation, weather/noise proofing element as well as bearing the loads of a building. Thus, it is necessary to design BIPV façade system so that PV systems itself complies all necessary factors of a façade. Warm façade systems usually cover all characteristic necessities of a façade system according to the architectural need. Cold façade systems that look opaque require a gap between the wall and the frame of the PV cladding panel for the air ventilation. They have limited aesthetic design options, however, cladding these systems are easier than warm façade systems.

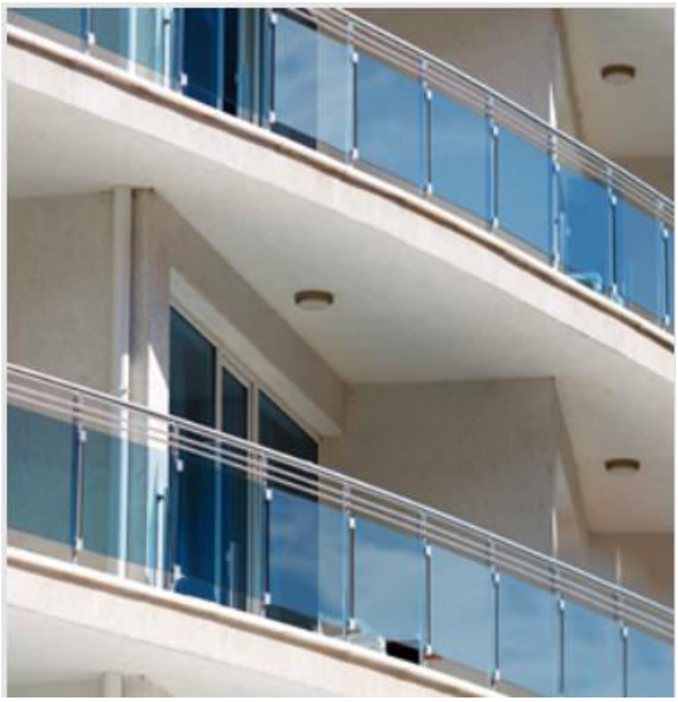


Figure 8. BIPV cladding systems (Topr-left: De Groot & Visser, Top- right: Sunpartner, Bottom: SELFA GE S.A) (Source: http://ashraemontreal.org)

Cladding systems are not the only option for BIPV application; solar glazing and windows, external devices and other building accessories such as parapets, sunshades, spandrels etc. (Fig. 8). Solar glazing systems can be used in skylights when PV system is laminated in glass-glass configuration; they can have a glazed look or have semi/full transparent design which can be considered for highly aesthetic architectural appearance.

Figure 9. BIPV Façade Systems. Top: Monte Rosa Hut, Zermatt (Switzerland), (Source: ETH Studio, 2009). Bottom: Meyer Burger Energy Systems, Switzerland (Source: http://www.solardistribution.eu/).

4.2. Coloured BIPV Implementations:

As it is mentioned earlier, market availability, competitiveness, and customer focused design let BIPV industry seek for more aesthetic choices. Researches also showed that roof-mounted BIPV applications are visually more appealing to the customers when the colour of the module is as same as the roof of their buildings [35]. Thin film technology can be manipulated to have different colour options for BIPV systems: for natural reddish colour hydrogenated amorphous Si (a-Si:H), for blue, purple, gold and silver coloured cells, hydrogenated amorphous silicon- carbide (a-SiC:H) can be employed as a reflective layer between front glass and transparent electrode [36]. Dye sensitised and thin film PV cells are naturally suitable for coloured applications, however, PV modules that are manufactured using first generation PV cells can be considered for coloured options. Despite that fact that using different coloured spectrum reduces the efficiency of the PV collector, roof or façade installations can be implemented to the point where low efficiency of the collectors can be tolerated by the area of implementation [31].

4.2.1. Thin Film Interference Coatings /Multi-Layer Interference Filters on Front Glass:

Visual appearance is confined since human eye can only detect a small fraction of light spectrum; this fraction can be manipulated by coating the glass with interference filters. Dr. A. Schüler developed a solution for reflecting specific part of the visible light while allowing the rest of the solar radiation wavelength to pass through by depositing nano-layers of TiO_2 and SiO_2. The numbers of TiO_2 and SiO_2 layers define the interference filter's applicability by shifting the coloured reflection of a spectral band as it is shown in Fig. 10 (top). When it is applied, interference filters give BIPV systems a glazed effect that slightly changes due to angle of vision [37]. The change of the angle visually defines the colour of the filters (Fig. 11).

Multi-layered reflective coating in front of PV module front glass is first offered in market as Kromatix^{TM} technology by SwissINSO (Fig. 12) and this optical layer give front glass a glazed look (Fig. 10, bottom) A multi-layered coating is deposited on the inner surface by low pressure plasma processes which gives the glass high transmittance (Emirates Insolaire LLC) [31].

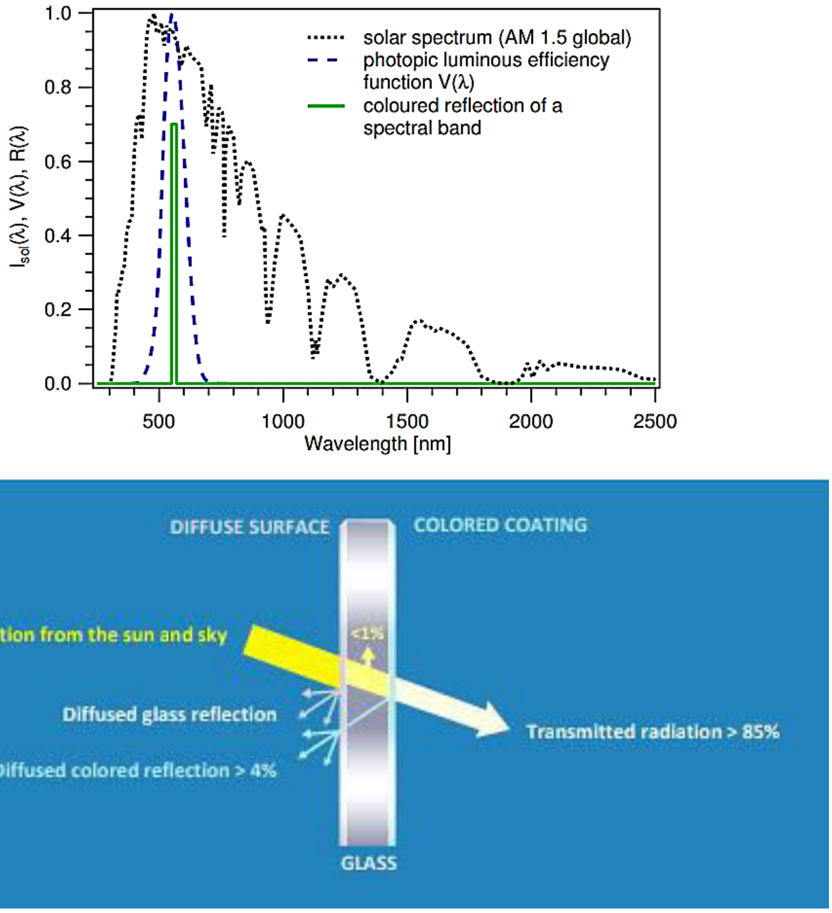


Figure 10. Top: Principle of coloured coatings for solar collectors (Mertin, S. (2015)), Bottom: KromatixTM interference filters principle (Emirates Insolaire LLC).

Figure 11. Colour coated glass with high transmittance (Source: SwissInso).

Figure 12. Location: Copenhagen, Denmark, Kromatix™ Glass: Blue Green, Surface Area: 6,048 sqm, Installed capacity: 1,030 kWp (Source: SwissInso).

Figure 13. Basel, Switzerland, Kromatix™ Glass: Grey, Blue, Blue Green and Gold, Surface Area: 159 sqm, Installed capacity: 24 kWp (Source: SwissInso).

Commercial BIPV fully integrated application that has been made in Gundeldinger Feld in Basel (Fig. 13) indicates the direct association between power yield and colour. Black modules with 14.6 kWh/m^2 power output (100% yield) as being the reference; green modules with 12.3 kWh/m^2 power output (91% yield), blue modules with 11.7 kWh/m^2 power output (87% yield), grey and gold modules with 11.1 kWh/m^2 power output (83% yield) has produced in between March 2016 and June 2016 [38].

4.2.2. Coloured Solar Cells:

Anti-reflective coating, usually prepared from silicon- nitride transparent dielectric material, on the crystalline solar cells defines the colour which is adjusted according to maximum photocurrent generation. The thickness of the coating could be manipulated to shift the reflective wavelength from around 700 nm to near infrared range so that usual colour of c-Si cells-black or bluish black- could be turned into different colours such as red, green, gold, purple etc. [39]. The price for coloured c-Si solar cells is way more expensive than conventional c-Si solar cells; hence, the market for varied coloured cells is still stationary. Visual representation of coloured solar cells and roof mounted application is shown in Figure 14.

Figure 14. Left: Coloured Solar Cells (Source: Lof Solar Coorperation) Right: Coloured PV cell application (Source: BISOL).

4.2.3. Coloured/Tinted Front Glass:

Using tinted float glass for front glass with colour options could be a solution for coloured BIPV application. Some PV module manufacturers use processed glass such as sandy glass or silk glass to reduce glaring effect and to give more visually aesthetic appearances. Usually, to obtain maximum yield from solar cells, front glass with 3.2 mm thickness is preferred be white, with low iron-oxide content (<0.1 % Fe_2O_3) and high transmittance. Power output for c-Si modules was observed to decrease with the iron content increase; which is why using regular tinted tempered glass is less preferable option for coloured BIPV than other options [40].

4.2.4. Ceramic Digital Printing on Front Glass:

Partial digital printing on front glass is becoming a new trend in architectural design of BIPV applications. Printing on glass technique implements visual aesthetics on especially façade systems and skylights that require unique solutions. Digital ceramic printing is a merge technology between ceramic silkscreen printing which is an old analogue process using ceramic ink and digital printing that is used possible organic inks such as solvent, water-soluble, UV- cured etc. Ceramic ink pigments are sprayed through multi-nozzle print heads onto float PV glass, preferably covering the glass partially enabling the light gets through the printing [41]. The most common pattern for digital ceramic printing is found as dots and commercially applied on façade systems as it can be seen in Figure 15.

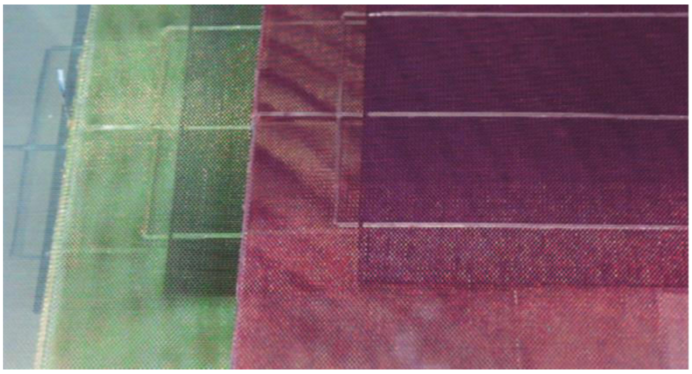
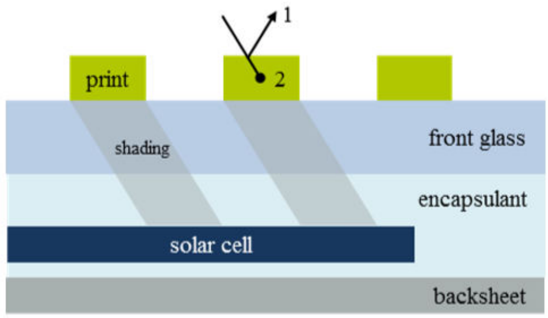


Figure 15. PV cells with ceramic digital printed front glass (Source: Left: SmartFlex Solarfacades), Right: Solar Silo (Basel)).

The design of printing, the angle and printing degree (from 0% to 100% coverage), thickness of the pattern, printing position (inner or outer surface of the front glass), and colour of the printing directly affect the efficiency of the PV module. According to Mittag (2017) [42], power output of PV module decreases by the printed ceramic ink that causes both shadowing solar cell, refracting the light (1) and absorbing light (2) (Fig. 16, left). On the other hand, it is also found that even transmittance values alone is affected by coverage ratio of the glass, it is insufficient to predict a direct link between BIPV module power and coverage ratio.

There has been some researches regarding of investigating the effect of pattern type, printing colour, printing coverage (fraction of printed versus un-printed area), and printing position (printing on the outer surface where is exposed to environment versus inner surface where is attached to encapsulant material). P. Bonomo and his team in SUPSI also covered some experiments on coverage and colour of the printing effects on power output; they found out the colour of the printed pattern significantly affects module power output (Fig. 16, right), meanwhile printing on outer side front glass gives only 1% bigger power output results than printing on the inner side of the glass [43]. However, findings from G., C. Eder et al. experiments contradict the result of previously mentioned experiments on the effect of printing on different plane of the glass. In these experiments, four white coloured patterned (chessboard and pressboard) glass is laminated on the cells and it is evidently shows that the efficiency losses is slightly higher (~32% loss) when the pattern is on the outer surface, than when it is on the inner surface (~28%) of the front glass [44]. Thus it seems important to investigate more on this subject matter in order to get more data.



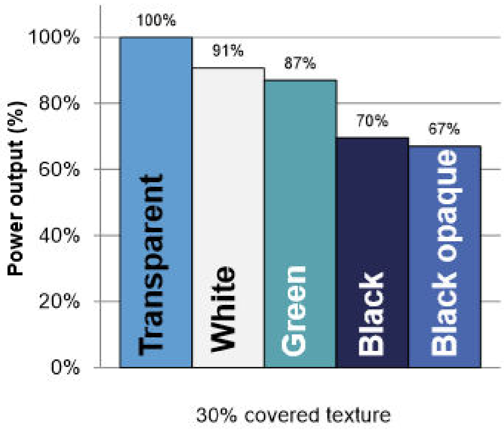


Figure 16. Left: Schematic drawing of changes in module optics by application of decorative prints onto the module front cover (M. Mittag et al., 2017). Right: Colour texture effect on power output (%) (P. Bonomo, SUPSI, 2017).

It is also worth noting that ceramic ink colour code for printers use CMYK code and any RAL code that matches for desired colour scale will not match with initial colour after lamination. The reason for that is because after lamination, last apparent colour for PV module is the combination of the opaque colour of PV cells, backsheet, wiring, and translucent colour of the front glass. Some researches for matching colour of the printing to PV module has been done to help finding optimum RAL code for manufacturers [45], [46].

4.2.5. Coloured Encapsulant and Other Special Intermediate Foil:

Conventional (c-Si) PV modules simply feature with low-iron float front glass, polymeric encapsulant, c-Si solar cells soldered bus bars that electrically connect cells to each other, and backsheet layer which can be polymeric, glass, metal etc. (represented in Fig. 1). Encapsulant material has great importance; it has to minimise interface reflectance, provide low light absorption and thermal conductivity, has to guarantee to maintain strong adhesion to other module elements and has to have strong stability for temperature changes, humidity and UV radiation [47].

PVB, a thermoplastic material, is a popular safety glass sealing and laminating compound for automotive and architectural application; making it better candidate for thin film BIPV technology due to the fact that thin film technology uses glass- glass encapsulation. EVA which belongs to thermosetting material with the addition of cross linking agent, however, is still the most popular and the cheapest option for BIPV market [48]. EVA films are usually preserved as opaque white or transparent when and due to aesthetic concerns, different coloured EVA films can be used for BIPV applications, whereas different coloured EVA foils are also available for other lamination applications. EVA is, in general, more resistant than PVB when exposed to moisture at open edge. It remains to be determined the quality of each individual EVA in the existing market.

The possibility to use luminescent organic dyes doped EVA encapsulation is documented in research activities [49]. Using other options for encapsulation rather than EVA and PVB has been investigated; coloured silicon encapsulant for PV module lamination is managed performing better than standard EVA film, due to their transparency [50]. On the other hand, using other encapsulant such as silicon-ionomer-polyefine based foils is still considered expensive and rather a new technology in the BIPV market; thus it is needed further investigation.

Some other innovative films have been developed by PV module manufacturers. Specially developed foils that are laminated with other elements of PV module give different colour option or visual instead of black and bluish colour. Film that has developed by CSEM, Centre Suisse d'Electronique et de Microtechnique, is laminated between c-Si solar cells and front glass after a high resolution photo is printed on the it; giving any possible look for façade systems. Solaxess (Fig. 18) also followed similar approach to develop a film that scatter the visible light while transmitting infrared; giving 'white module' appearance.

Figure 17. BCN, Banque Cantonale Neuchâteloise (Source: Kaleo Solar).

In Figure 17, the photo that was printed on the front glass by using ceramic digital printing technique is represented. Behind each photo, mono-crystalline solar cells are hidden for active energy supplier as PV modules.

Figure 18. JDSA Julien de Smedt Architect, Cebra, LPA (Source: Solaxess).

5. DESIGN DEVELOPMENT PROCESS:

5.1. Coloured Solar Cells:

Estimation for visual evaluation on metal backsheet and coloured cell matches are visualised and investigated using AutoCAD before module manufacturing. It can be seen in Figure 19 that some metal backsheet colours blend in for solar cells that are preferred for this thesis. For coloured multi-crystalline solar cells, 6’’ classical series with 4 BB (busbar) from LOF Solar Corp. is chosen. Since blue silicon nitride anti-reflection coatings give them significant colour; glazing occurrences were also worth to test for visual evaluations. For this purpose, each solar cell that has different colour is laminated just with POE, 3.2 mm thick low iron, tempered float glass with sandy surface, and backsheet. Three different PET backsheet colours were picked (black, white, and dark grey) to observe glazed effect better (Fig. 21). Glazing effect of cells has importance for testing when cells are exposed to sunlight, hence all visual RAL code matches also concluded under day light, outside conditions by positioning each module in different angle (Fig. 20). After lamination, it was evident that visual evaluation by using AutoCAD shows similarities with real visual evaluation.

It is also important to note that, solar cells colour are dependent on the visual angle; hence it is not certain if metal backsheet matches give same effect when the modules are inclined on a rooftop.

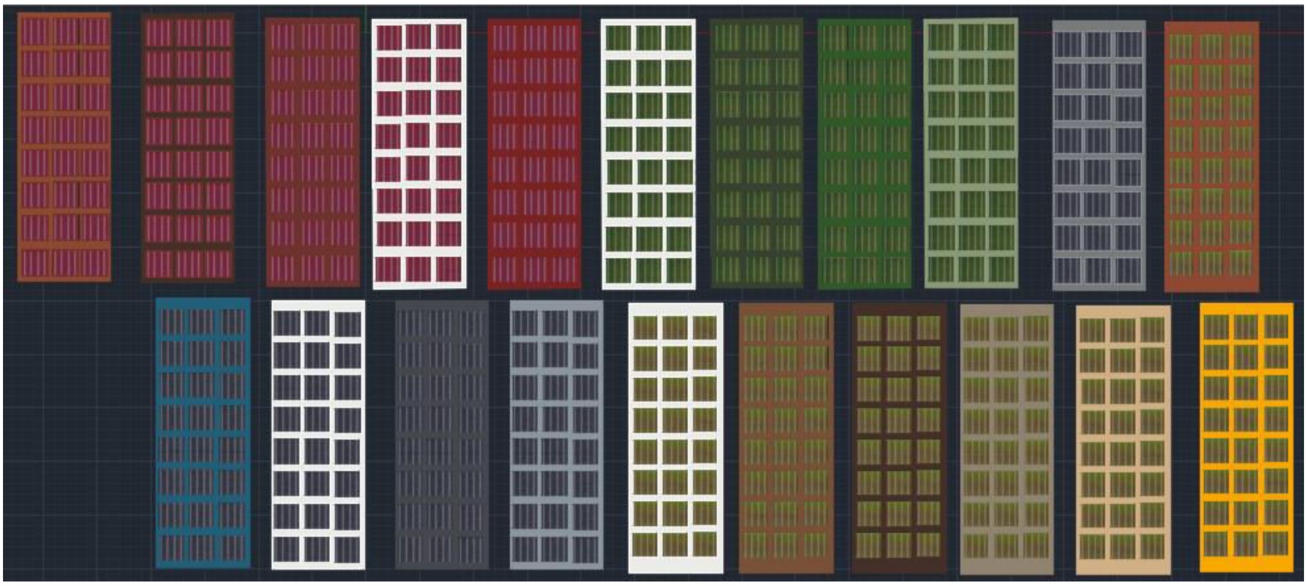


Figure 19. AutoCAD drawing for each LOF Solar Corp. classical series multi crystalline solar cells with matching metal backsheet.

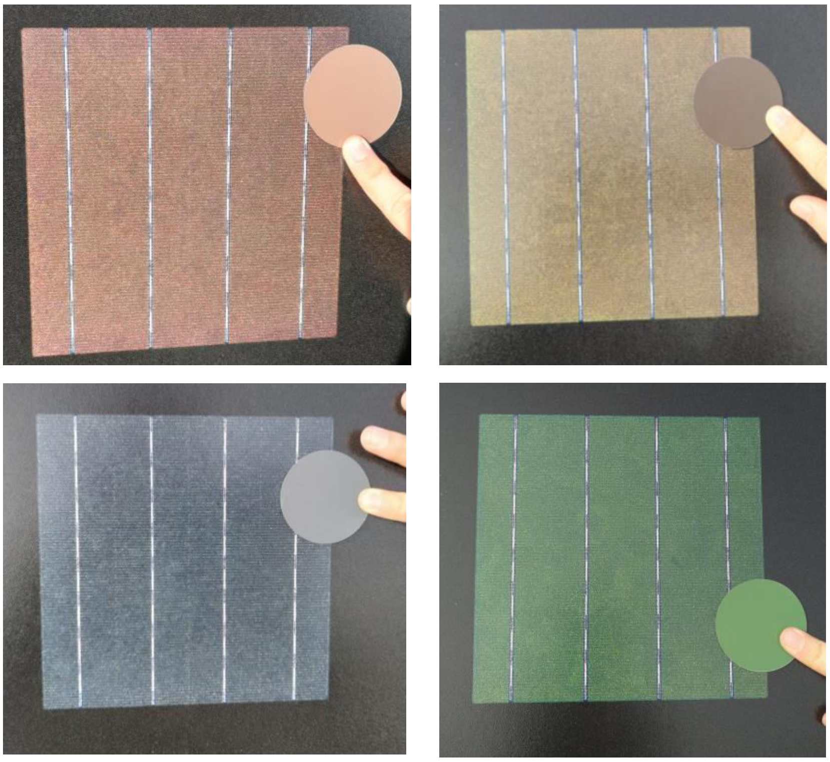
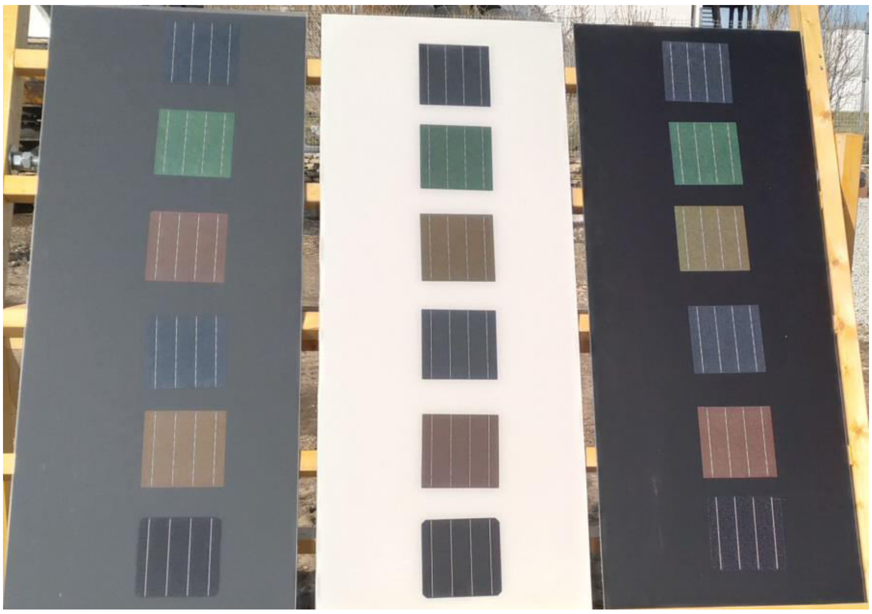


Figure 20. Colour matching tests with metal backsheet RAL codes after lamination.

Commercially, it is important to make cells blend in background roof colour; instead of using two of the most common backsheet colours (black and white) transparent backsheet is needed. It is important to note that except black, white and dark grey, there is no other coloured backsheet that are manufactured for PV industry. Thus, using transparent backsheet and coloured metal backsheet together is essential for the most visually appealing option



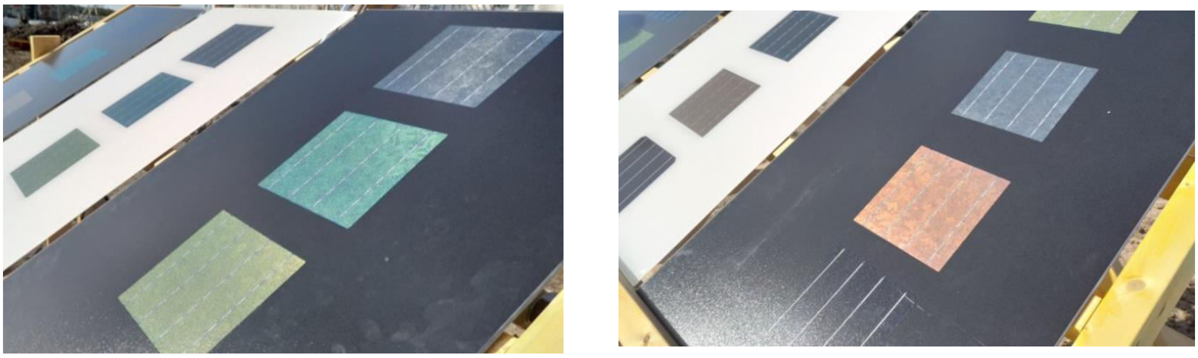


Figure 21. Visual changes of coloured multi-crystalline PV cells due to scattering of light, inclination angle of the modules and exposure to sunlight.

After visual evaluations and metal backsheet, PV modules are laminated. For lamination, the design is considered as follows;

- transparent PET backsheet - one layer of POE - active layer (soldered in three parallel lines that consist of eight cells) - one layer of POE - front glass (3.2 mm thickness, tempered low iron float glass with sandy surface on both sides).

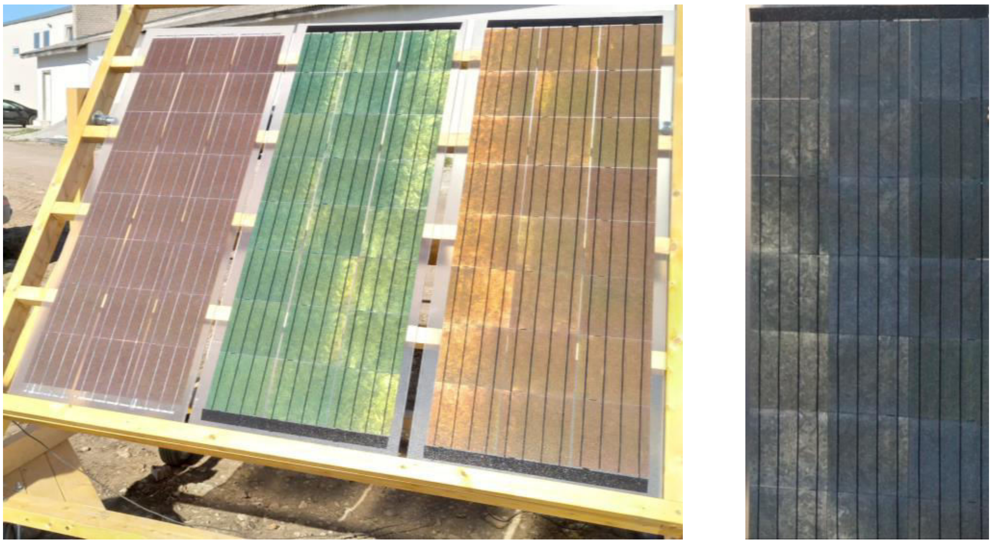


Figure 22. Modules with laminated coloured solar cells.

5.2. Coloured EVA Encapsulators:

As it is mentioned in Section 4.2.5, PV manufacturing industry only uses EVA with transparent/white colour which is mainly manufactured specially for PV industry; hence, coloured EVA has not been used for PV modules so far. For commercial success, it is important that each material for a PV module should last at least twenty years, including encapsulants. However, coloured EVA encapsulators that are mainly considered for interior design are less likely to expose outside conditions; they have lifespan of five to seven years. The difference between coloured EVA encapsulators for interior design and super clear EVA encapsulators for PV modules come from using different processing technologies to cover different requirements.

In order to make coloured EVA encapsulations on glass for indoor designs: first sheets combined each other to then place in silicone bag for pre-vacuuming, which needs 5-10 minutes. After vacuuming, the material is sent to furnace where the temperature of each stage is adjusted according to the glass surface temperature. First stage of the furnace takes place at 60 °C and 15 minutes and the second stage at around 120 °C. Heating preserves for 30 minutes; depending on the thickness of the glass, this time can vary. Finally cooling is operated till 60 °C to finish the glass encapsulation.

The most important parameter for coloured EVA encapsulation is to have a translucent characteristic so that PV cells can be still visible to sunlight to produce energy. For this purpose, bilateral negotiations have been made with several suppliers of coloured EVA foils that have transparency and after all negotiations, Luoyang Lever Industry Co. has supplied eleven different coloured transparent EVA films. Five base colours (red, blue, yellow, green, brown) that are most commonly used for metal roofs have selected for EVA foils and different shades of each have been ordered for tests.

Similar approach has followed for EVA foils as for coloured PV cells; colour visual tests have been made before manufacturing any module. Therefore, each foil are cut equally to be laminated together to operate in one module as it can be seen in Figure 23; 6’’ mono-crystalline PV cells with 4BB are used for lamination and a special design approach has been completed by soldering each cell to a silver ribbon that passes through the middle for current measurements. For reference, one cell is soldered without EVA foil (Fig. 24). Design of the module has been made as;

- 3.2 mm thick float/tempered glass with sandy surface-POE-one layer of EVA foil for each colour- soldered 6 ’’ mono-crystalline PV cells-POE- float low-iron, tempered glass with 3.2 mm thickness and sandy surface accordingly,

and lamination process is kept same as previous tests.

Figure 23. Module design for current tests and visual comparisons.

After lamination, visual evaluations and current measurements completed in outside conditions for different inclination angles. As in Figure 24, it can be seen that EVA encapsulation fails to cover PV cells and give very weak visual appearance; therefore the same procedure has been operated by using two layers of EVA foils for visual comparison.

Using double layers of EVA for lamination also does not give a satisfactory coverage for any PV cells, except green, red, dark grey EVAs. Thus, power output tests for EVA encapsulation has completed by using double layer green EVA encapsulant. For this purpose,

– transparent PET backsheet- POE foil- 6’’ mono crystalline PV cells- double layer of green EVA encapsulant-POE foil- 54x136 cm low iron, tempered float glass with 3.2 mm thickness and sandy surface on both sides have been used and power output measurements have been tested in outside conditions.

Figure 24. Left: Visual differences between laminating active layer of the module by using one layer EVA (on the left) and two layers of EVA foils (on the right) with green EVA encapsulated module. Right: Visual examination due to inclination changes.

5.3. Digital Ceramic Printed Front Glass:

Glass printing pre-reviews have been made for UV digital glass printing first. UV ink based printing that is popular among decorative glass manufacturing market can be also applied to PV module glass; however, UV inks are bonded only by surface chemistry; causing the printing fades away in three to five years in outdoor conditions. UV inks are also less abrasion resistant, which means digital printing requires some cleaning instructions.

On the other hand, ceramic inks consists of three parts: glass frits with inorganic pigments that melts into the glass, a resin that holds the frit in place prior to firing process, and a liquid medium which allows the ink to be applied. The liquid medium is mostly produced from water miscible materials; causing the ink requires high temperatures (160-180°) to dry. IR (Infrared dryers are more suitable for ceramic ink than UV dryers [52].

The ceramic ink is digitally applied via inkjets; depending on the printer, there are 8, 12, or 16 print-heads with 256 nozzles per head that imaging up high resolution. Ceramic digital printing is first processing the digital image through RIP, Raster Image Processor. RIPs simply convert PostScript codes (page description language /codes that consist of Bezier curves or ’vector’ codes that looks like arc/curve) into a matrix of codes ('raster' image that is rendered from 'vector' curve codes to pattern of dots) [53]. DXP image processing software converts standard graphic files into ready-to-print files optimized for glass. The software includes a Pattern Generator plug-in for Adobe Illustrator, automatic colour separation optimized for transparent media, and a colour atlas for converting RAL and Pantone colours [54].

The process after converting images is rather simple. First glass is washed and prepared for printing. As the images being printed, integrated inline dryer is used to dry the ink. The sensor-controlled IR-Dryer, positioned immediately after the printing area, dries the ceramic ink for dust-free operation. Finally, pigment-based ceramic ink is thermally fused into the substrate glass during tempering process [52], [54].

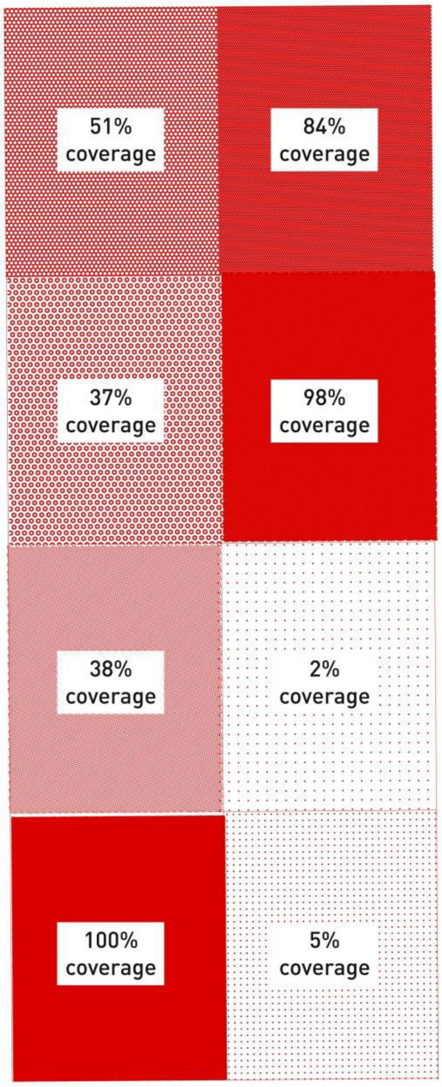
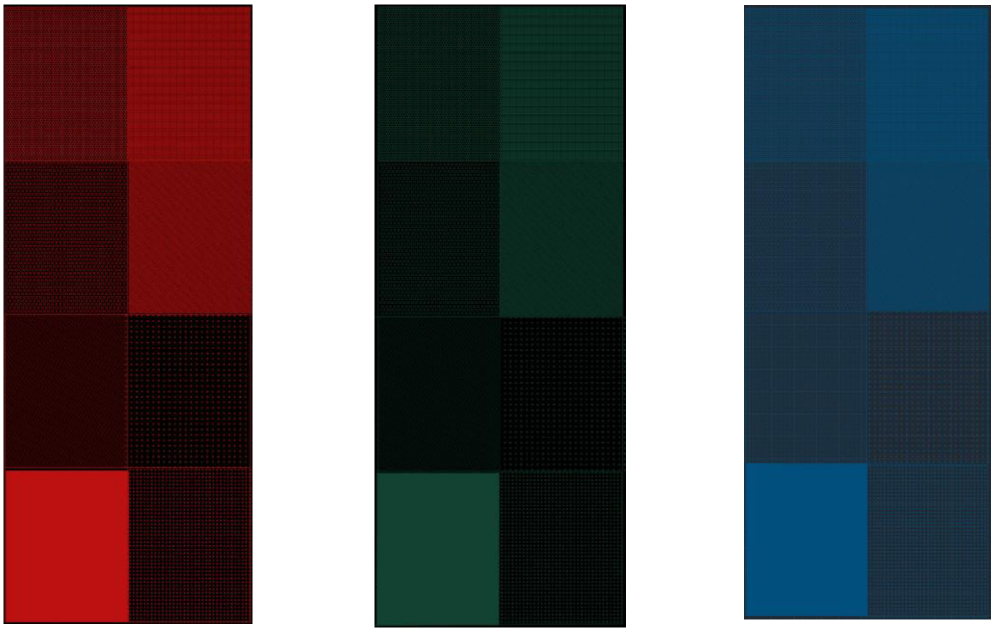


Figure 25. Coverage ratios of each pattern.

After market reviews, digital ceramic printing favoured over UV ink printing; thus Glas Trösch has accompanied to be cooperated for printing process over several other companies after negotiations. For visual and power output testing, different colours and different coverage ratios with different patterns were needed, so the AutoCAD design that covers each of these parameters has been made (Fig. 26). Six different glasses with equal size as in the previous tests (54x136 cm) have chosen and each glass has divided into eight equal sections; each having different coverage ratio and patterns (honeycomb, hexagonal, dot) (Fig. 25).

Six colours that have the same RAL code for metal roof colours are decided and the RAL codes are as follows: RAL 7010, RAL 9016, RAL 9002, RAL 6005, RAL 5010, and RAL 3020. To make sure sandy glass can be used for printing, roughness tests have completed, then twelve glasses have sent for printing; one for inner surface, and one for the outer surface of the front glass for each colour to be printed on.



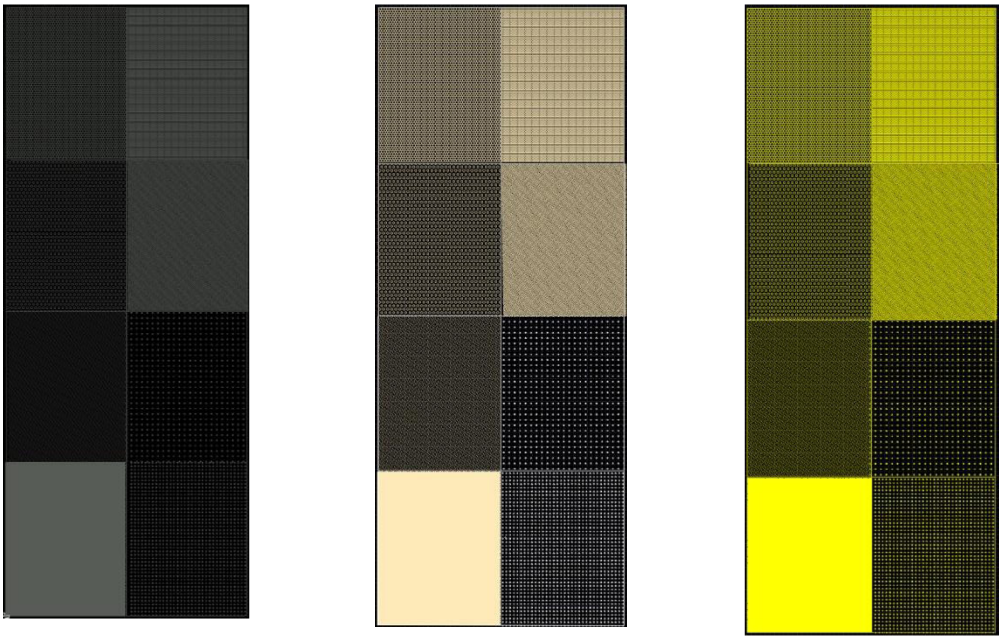


Figure 26. AutoCAD drawing for each colour for specific RAL codes

Since the patterns divide the front glass into eight different sections with different coverage ratio, it was clear that standard lamination as manufacturing PV modules would not give proper result for power output comparison and assessments. Therefore, two mono-crystalline solar cells connected in series are independently placed behind each covered section of the front glass and then laminated with adhesive (POE) and backsheet layer. As it is mentioned earlier, facing the printed surface on the outer side or inner side of the module has an importance in terms of both visual appearance and output power; hence, white coloured glasses are picked to compare the effect of printing on different sides.

In order to be converted all values to standard conditions (1000 W/m^2), irradiance and current measurement took place outside under the sun irradiation, and short circuit current (Isc) and irradiance (G) values are measured simultaneously with a reference cell by using solar irradiance sensor. After measurements, it was clear that the ceramic printing facing inner side of the front glass gives better visual short circuit current (Isc) output (Table 3), (Fig. 30). All other coloured glasses are laminated as printing would face outer side and measurements have been made accordingly. It was also clear that, sections that has 98% and 84% coverage give the best visual appearances. Moreover, colours of the glasses after printing do not match with the AutoCAD design drawing; even if the process has completed with the same RAL codes.

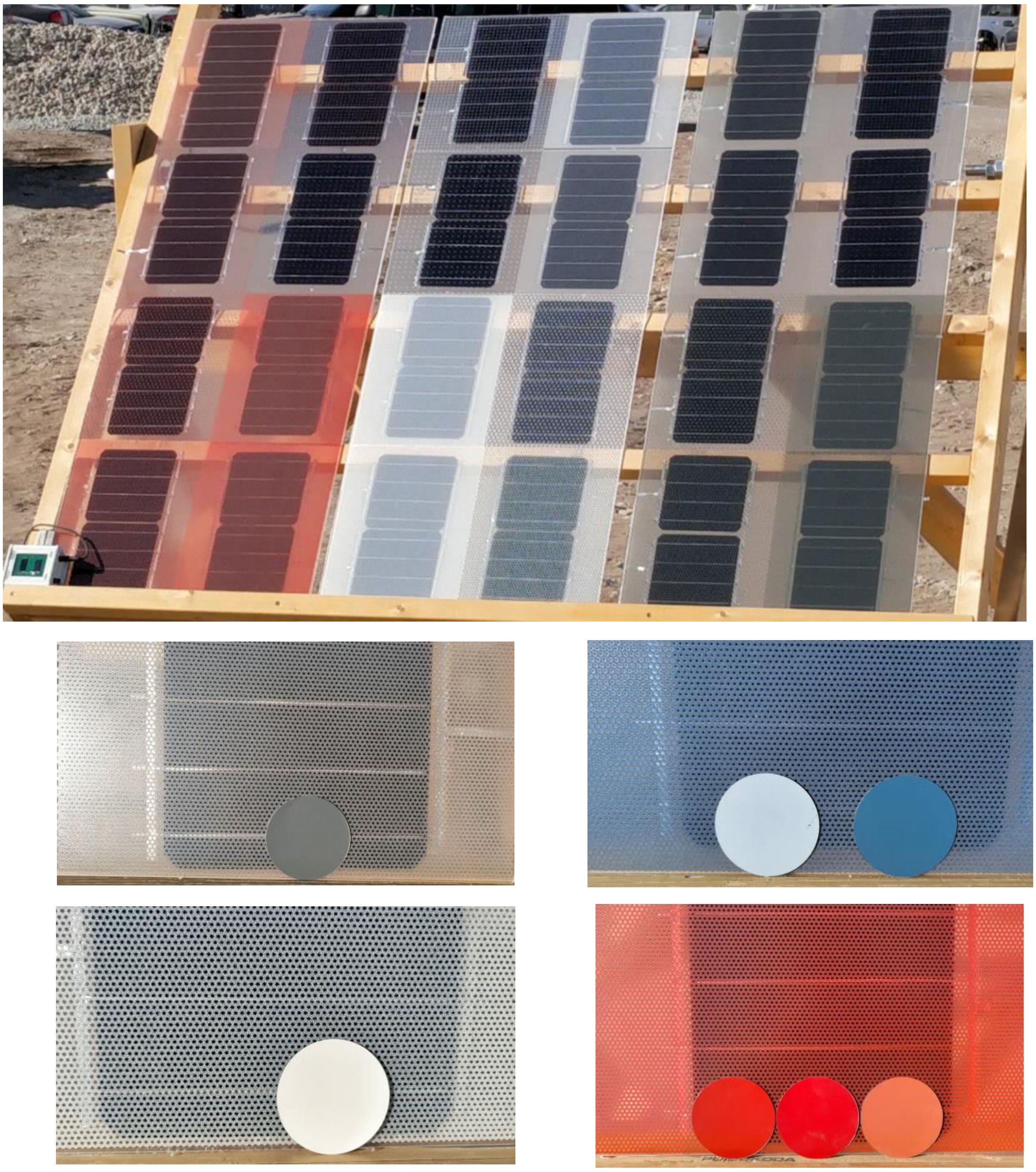


Figure 27. Module with digital ceramic printed front glass and coloured metal backsheet RAL code match test

5.4. Special Encapsulant Foil:

In this thesis, Solaxess white solar encapsulant that is specially designed as the company trademark has been tested for alternatively coloured BIPV module. As it was briefly mentioned in Section 4.2.5, Solaxess foil reflects visible light and transmit infrared rays which allows PV modules to appear white to the human eye. It is also mentionable that due to colour, the film also reduces the module's operating temperature 10° which can lead to have a better relative performance in warm climates [55]. The special encapsulation is processed into lamination as follows:

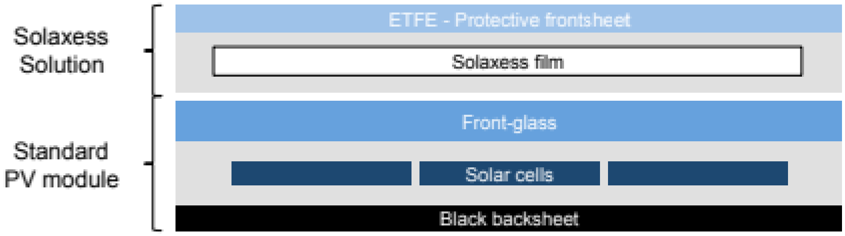


Figure 28. Schematic representation for lamination of a special encapsulant foil [55].

Current measurements have been accomplished by laminating 'white' encapsulant as a small sample with POE and samples glass and the result have been compared with reference sample with both 6'' mono-crystalline PV cell and same PV cell behind sample glass in outdoor condition (Fig. 29).

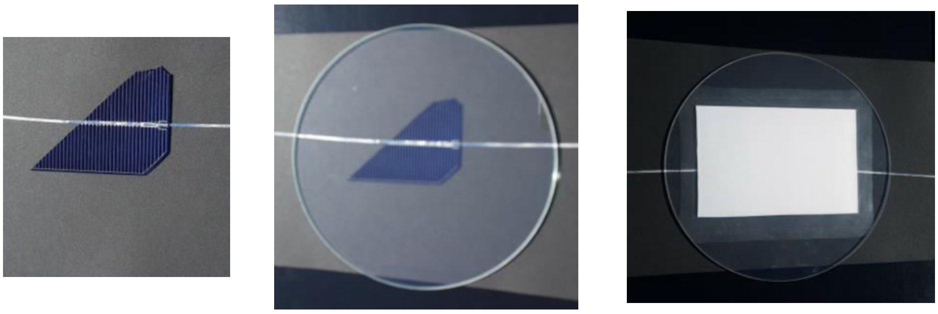


Figure 29. Current testing for with special encapsulant, sample glass and reference sample PV cell.

The results for current measurements will be presented in Section 6.1. Power output tests are conducted after lamination of the module by using the referenced technique by Solaxess.

5.5. Interference Filters:

Interference filters are specially designed for a defined angle of incidence of the illumination beam; if the angle of incidence or angle of aperture changes, then the optical properties of the interference filter will change as well. These changes depend on the spectral position of the filter the state of the polarisation of the radiation, the materials used for the layer and the design of the filter systems as a whole. Hence, it is important to define the wavelength, transmission values as well as blocking/reflection requirements for each filter to specifically design for PV integration. CWL (central wavelength) of bandpass filters in this case is known to be 550 nm for visible light range; however, transmission values can vary according to the design requirements.

Interference filters for PV integration can be accomplished by simply replacing the bandpass filter as a front glass or placing the filter in front of the front glass of the module. The biggest drawback of this of this option is the price. The filter for 54x136 cm sized glass costs 2000-5000 € depending on the price offers; thus, interference filters are eliminated from the manufacturing process in this thesis.

6. TECHNICAL AND ECONOMICAL EVALUATION:

6.1. Technical Results and Evaluation:

The performances of each manufactured PV module are evaluated using Photovoltaic Panel Analyser and the results are transformed to STC (25°C and 1000 W/m^2). The instabilities of solar irradiation due to cloudy weather or inclination angle differences can be fixed by using Photovoltaic Panel Analyzer which has constant solar irradiance within testing time of period. Moreover, data comparing PV module performance assessments are made correspondence to a reference module that was manufactured without using any material that was specifically evaluated for this thesis.

Current measurements for EVA foils and Solaxess intermediate foil have been evaluated according to the sample testing as it was mentioned in the previous sections. Current measurements results have shown that current of Solaxess intermediate foil is 2.5 times less than sample cell with sample glass. The results are presented in Table 1.

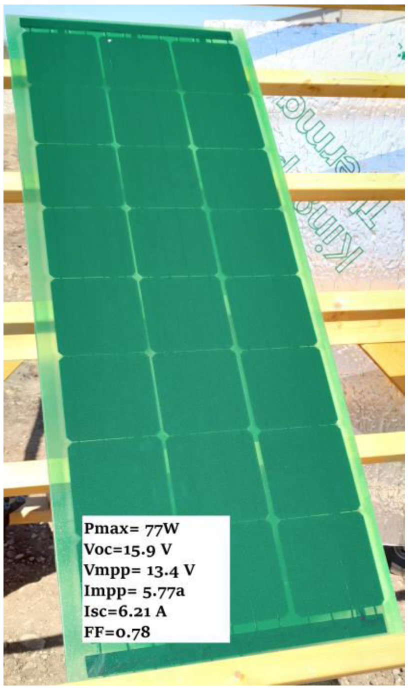
Table 1. Current measurements of sample and reference cell for Solaxess intermediate foil.

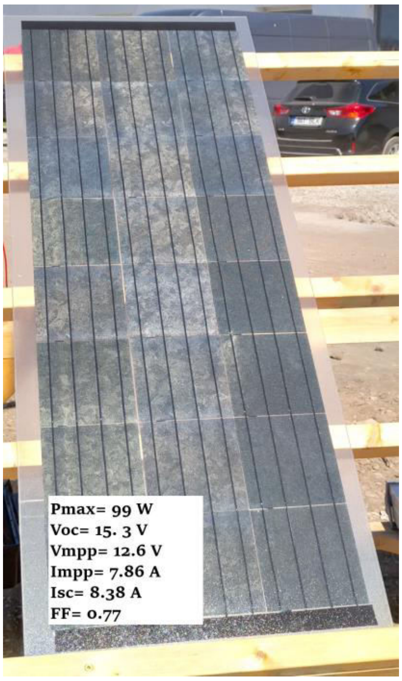
	Reference cell without glass	**Reference cell with glass**	**Cell with Solaxess foil**
Ave. Current (A)	8.1	7.3	2.9

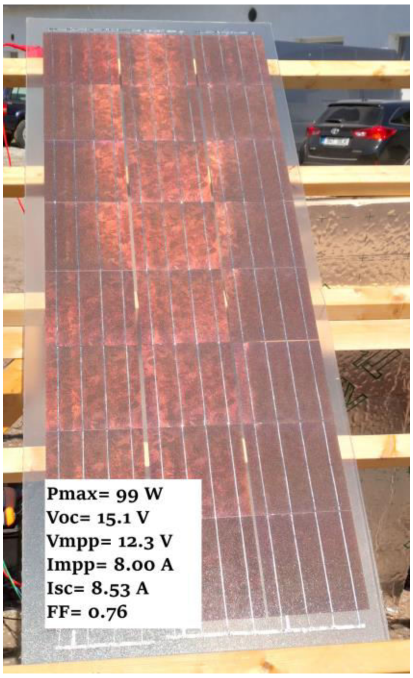
Special module design that was described in Section 5.2 for EVA encapsulation is also taken place for current measurements and the results are as follows:

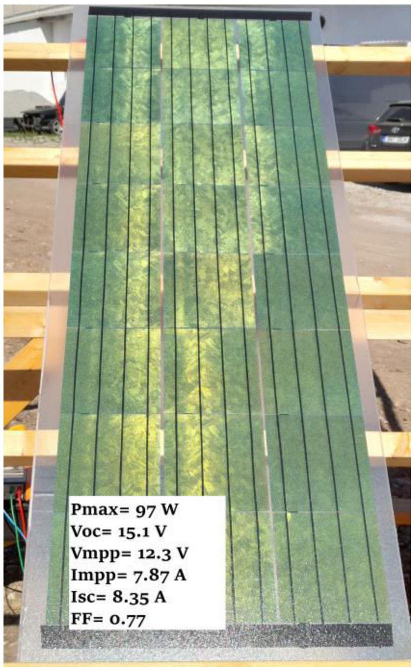

Pmax= 99 W
Voc = 15.4 V
Vmpp= 12.4 V
Impp=8.00 A
Isc=8.88A

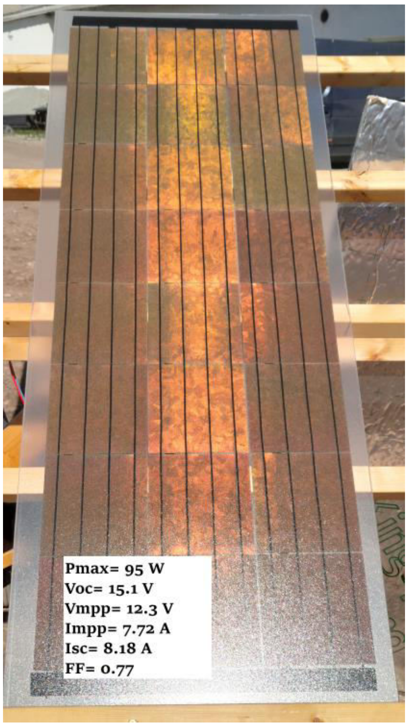

Pmax= 63 W
Voc= 15.6 V
Vmpp= 12.8 V
Impp= 4.90 A
Isc= 5.18 A
FF=0.78

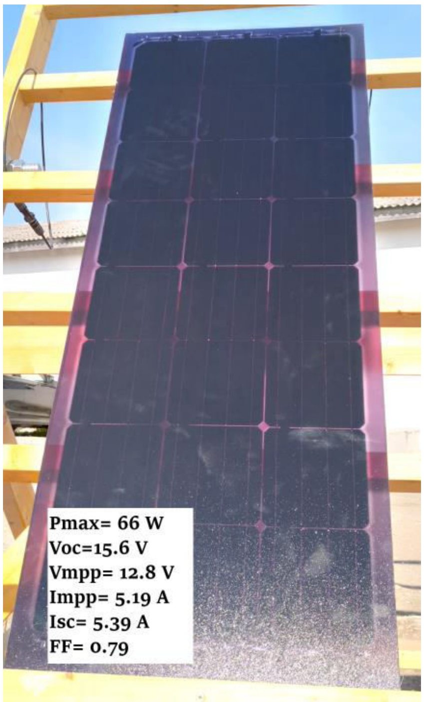

Pmax= 77W
Voc=15.9 V
Vmpp= 13.4 V
Impp= 5.77a
Isc=6.21 A
FF=0.78


Pmax= 99 W
Voc= 15. 3 V
Vmpp= 12.6 V
Impp= 7.86 A
Isc= 8.38 A
FF= 0.77

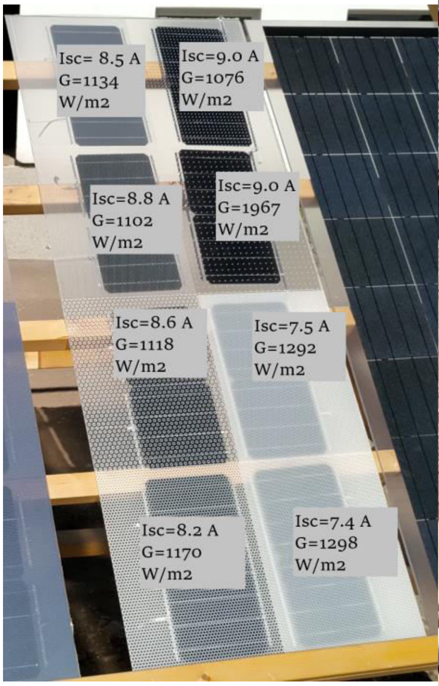

Pmax= 99 W
Voc= 15.1 V
Vmpp= 12.3 V
Impp= 8.00 A
Isc= 8.53 A
FF= 0.76

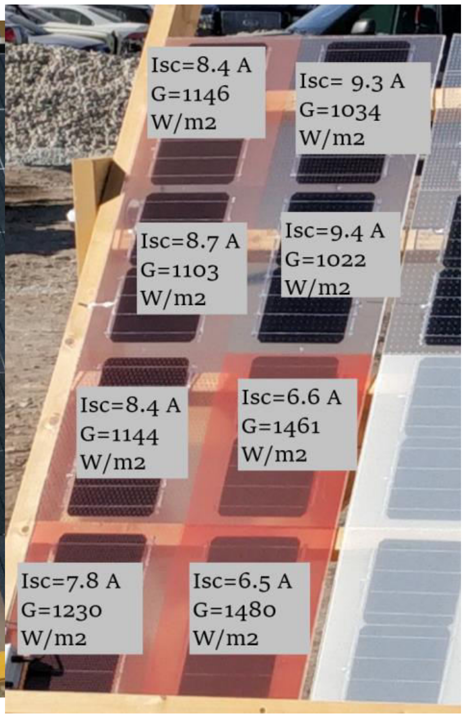

Pmax= 97 W
Voc= 15.1 V
Vmpp= 12.3 V
Impp= 7.87 A
Isc= 8.35 A
FF= 0.77


Pmax= 95 W
Voc= 15.1 V
Vmpp= 12.3 V
Impp= 7.72 A
Isc= 8.18 A
FF= 0.77


Pmax= 66 W
Voc=15.6 V
Vmpp= 12.8 V
Impp= 5.19 A
Isc= 5.39 A
FF= 0.79


Pmax= 73 W
Voc= 15.7 V
Vmpp= 12.9 V
Impp= 5.65 A
Isc= 5.76 A
FF= 0.81


Isc= 8.5 A G=1134 W/m2
Isc=9.0 A G=1076 W/m2
Isc=8.8 A G=1102 W/m2
Isc=9.0 A G=1967 W/m2
Isc=8.6 A G=1118 W/m2
Isc=7.5 A G=1292 W/m2
Isc=8.2 A G=1170 W/m2
Isc=7.4 A G=1298 W/m2


Isc=8.4 A G=1146 W/m2
Isc= 9.3 A G=1034 W/m2
Isc=8.7 A G=1103 W/m2
Isc=9.4 A G=1022 W/m2
Isc=8.4 A G=1144 W/m2
Isc=6.6 A G=1461 W/m2
Isc=7.8 A G=1230 W/m2
Isc=6.5 A G=1480 W/m2

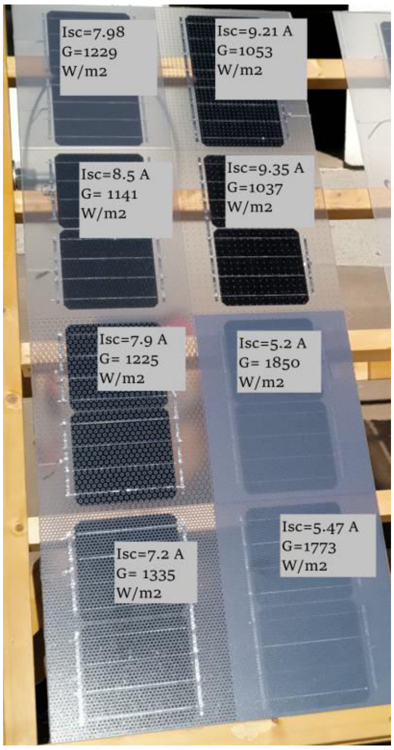

Isc=7.98 G=1229 W/m2
Isc=9.21 A G=1053 W/m2
Isc=8.5 A G= 1141 W/m2
Isc=9.35 A G=1037 W/m2
Isc=7.9 A G= 1225 W/m2
Isc=5.2 A G= 1850 W/m2
Isc=7.2 A G= 1335 W/m2
Isc=5.47 A G=1773 W/m2

Figure 30. Power output assessments for each manufactured module.

The measured data for current, voltage and power output can be different from the theoretical values. In Figure 30 and Table 2, it can be seen that experimental and cell-to-module output results do not match. Low power output values also in result of internal resistance of series connected PV cells and power output measuring devices. Optical losses due to the sun refraction of the front glass causes the nominal power drops 10% as well as with the mismatch losses of the series connected solar cells with different current values.

As for the modules that are laminated with coloured EVAs, the main reason for the power output mismatches occur due to cell cracks. For manufacturing these modules, the same lamination arrangement/ design were prepared; using one layer of POE as an adhesive layer. However, due to soft characteristics of EVA foils, the solar cells cracked during vacuuming of the lamination process. After that, two layers of POE was arranged for the same design structure and laminated under longer vacuuming time by changing the lamination recipe. Unfortunately, the stiffness of the lamination process did not change the result; even after the lamination recipe was changed, small cracks on the cells were observed in each module. Thus, it is evident that vacuum pressing of the laminator cannot be soften by neither putting more adhesive layers or by extending vacuum time in the lamination recipe.

Theoretically, each panel that is laminated by using mono-crystalline cells should give 120 W output power; connecting twenty-four cells in series that have 5.0 Wp for each. Other coloured module options such as Solaxess and coloured EVA encapsulated modules are also considered giving 120 W output power theoretically since the same mono-crystalline cells are used for their manufacturing.

Table 2. Theoretical and experimental power outputs for each manufactured module.

Module for Solar Cell Type	Sum of the Cells Power Output (W)	Experimental Power Output (W)	Cell-to-module Loss (%)
Reference module	120	99	17
Solaxess module	120	63	47
Green EVA encapsulated module	120	77	35
Red EVA encapsulated module	120	73	39
Grey EVA encapsulated module	120	66	45
Tile red multi-crystalline cell	108	99	8
Forest green multi-crystalline cell	107	97	9
Golden brown multi-crystalline cell	108	95	12
True steel multi-crystalline cell	107	99	7

According to the calculations, cell-to-module loss for Solaxess module is found the best the highest loss; 47% of the nominal output power is lost due to the coverage and the film with interference filter. Reference module lost 17% of its nominal power, this was an expected result in terms of 10% of optical losses and mismatch losses as it was briefly mentioned earlier in this section.

Table 3. Current measurements for comparing the effect on facing the printing to different sides of the front glass.

	Facing to the outer side		Facing to the inner side	
Coverage ratio (%)	Current (A)	Irradiance (W/m^2)	Current (A)	Irradiance (W/m^2)
5	9.01	1076	9.29	1047
100	8.55	1134	8.80	1101
2	9.09	1067	9.30	1042
38	8.80	1102	9.01	1076
98	7.51	1292	7.70	1259
37	8.68	1118	7.91	1226
84	7.47	1298	7.73	1255
51	8.29	1170	8.59	1129

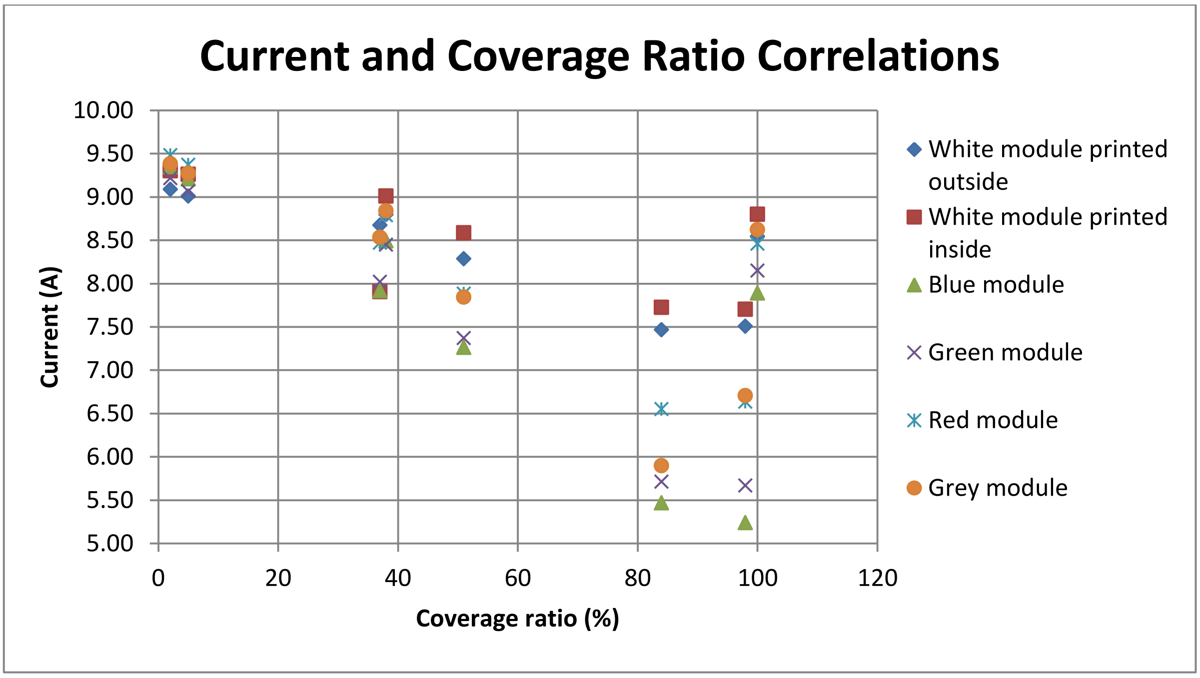


Figure 31. Current and coverage ratio correlation for each coloured module with digital ceramic printing front glass.

Modules with digitally ceramic printed front glasses, 84% or 98 % coverage for each colour give the best result. For 84 % coverage, the highest current is reached by white coloured modules gave the highest Isc value; printing facing inner side is measured as 7.7 A, and facing outer side is measured as 7.4 A short circuit current. Red, grey, green, and blue coloured modules are followed white coloured modules by having 6.4, 5.9, 5.7, and 5.4 A respectively. The correlation between coloured, coverage ratio and current values are given in Figure 31.

There are inconsistencies with the measurements in terms of coverage ratio, printing plane differences and colour types. Coverage ratio for each section on the front glass was experimentally matching with the AutoCAD drawing ratio. In the AutoCAD drawing 100% coverage was achieved (Fig. 25); however, it was experimentally observed that the pattern does not cover the whole glass as in the drawings, and all other coverage also have a ‘see through’ transparency. Other inconsistencies with the correlations and values are found to be due to different spectrum of the irradiation difference during, and temperature differences of the outside condition.

Table 4. Cell-to-module ratio for each coverage area according to STC of each coloured module with digital ceramic printed front glass.

	Cell-to-module Ratio					
Coverage Ratio (%)	**White on outer side**	**White on inner side**	**Blue**	**Red**	**Green**	**Grey**
5	0.93	0.95	0.95	0.97	0.93	0.96
100	0.88	0.90	0.81	0.87	0.84	0.89
2	0.94	0.95	0.96	0.98	0.95	0.97
38	0.91	0.92	0.88	0.91	0.87	0.91
98	0.77	0.79	0.54	0.68	0.58	0.69
37	0.89	0.81	0.82	0.87	0.83	0.88
84	0.77	0.79	0.56	0.68	0.59	0.61
51	0.85	0.88	0.75	0.81	0.76	0.81

In Table 4, it is evident that cell-to-module ratio has the lowest when the colour is blue, which has a parallel result with current measurements with giving the lowest current value among others when the coverage is 84 %. White coloured front glass that is laminated when printing is on the inner side has the highest cell-to-module ratio than the printing facing on the outer side, however, spectrum of the irradiance differences and temperature differences may affect this result as it was mentioned earlier. As it can be seen in all cell-to- module ratio values when the coverage is 100 %, the values are higher than expected; this is also another evident that the printing has transparency.

6.2. Economical Results and Evaluation:

Economical evaluations have been compared according to a reference PV module that was structured in manufacturing process. Prices for each material that is used to manufacture the reference module are shown in Table 5 below:

Table 5. Material costs for the reference PV module.

Material	Price	Amount	Price for one module (€)
Coloured metal backsheet	9 (€/m^2)	0.73 m^2	6.62
POE	1.7 (€/m^2)	2.19 m^2	3.72
Black PET backsheet for insulation	2.2 (€/m^2)	0.73 m^2	1.62
Transparent PET backsheet for insulation	6.78 (€/m^2)	0.73 m^2	4.94
4BB solar cells	1.06 (€/pcs)	24 pcs.	25.44
Silver ribbons for soldering (thin and thick)	0.31 (€/m)	33 m	10.23
Black tape for silver ribbons coverage	2.77 (€/m)	1.65 m	4.58
Front glass	7 (€/panel)	1 pcs.	7.00
Junction box	2.25 (€/pcs)	3 pcs.	6.75
	COST (reference module)		65.96
	COST (others)		69.28

As it can be seen from Table 5, the cost for manufacturing one PV reference module with the size of 54x136 cm and eight cells connected in the line of three is 65.96 €. For reference module, black PET backsheet is used instead of transparent PET backsheet For other coloured PV modules, transparent PET is considered to see coloured metal backsheet matches and without any special material, one module with transparent PET backsheet costs 69.28 €. Different materials that have been ordered for this thesis and cost for one manufactured module for each are given in Table 6 below. The cost for each option is calculated by adding 69.28 € as total cost for one module without any special material.

Table 6. Prices for each material that have been used to manufacture and the cost for one module for each coloured BIPV module option.

Material	Price	Amount used for one module	One Module Cost* (€)	ONE MODULE COST (€/Wp)
Coloured (Green) EVA Foils	7.6 ($USD/$m^2$)	$2.19_{\text{double layer}}$ (m^2)	83.09	1.07
Coloured (Red) EVA Foils	7.6 ($USD/$m^2$)	$2.19_{\text{double layer}}$ (m^2)	83.09	1.13
Coloured (Grey) EVA Foils	7.6 ($USD/$m^2$)	$2.19_{\text{double layer}}$ (m^2)	83.09	1.25
Tile Red Solar Cells	0.80 ($USD/Wp)	100.08 ($Wp_{24\ pcs.}$)	136.41	1.37
Golden Brown Solar Cells	0.80 ($USD/Wp)	100.08 ($Wp_{24\ pcs.}$)	136.41	1.43
True Steel Solar Cells	0.80 ($USD/Wp)	106.08 ($Wp_{24\ pcs.}$)	140.43	1.41
Forest Green Solar Cells	0.80 ($USD/Wp)	106.08 ($Wp_{24\ pcs.}$)	140.43	1.44
Solaxess Intermediate Foil	100 (€/m^2)	0.73 (m^2)	142.28	2.25
Digitally Ceramic Printed Glass	108.75 (€/pcs)	1 (pcs.)	178.03	2.64- blue 2.18- red 2.5- green 2.4- grey
Interference Filters	2000-5000 (€/pcs)	-	~5000	-
Reference Conventional Module				0.66

*Conversion for one USD to Euro is calculated as 1USD= 0.838 €.

According to the prices, it can be seen that EVA foil is the most cost effective option for coloured PV module design whereas the most expensive option is digital ceramic printing process. It can also be seen that coloured solar cells are almost three times more expensive than conventional mono-crystalline solar cells. Interference filters are not included in the manufacturing process, since they are extremely expensive for commercial scale manufacturing. For digitally ceramic printing, one module cost for one Wp is calculated by choosing best visual conversion which was 84% coverage ratio and it is calculated for each colour except white.

7. CONCLUSION:

In this work, coloured PV modules that can be mounted on metal roofs in are investigated in the case of commercial scale manufacturing. For this purpose; multi-crystalline solar cells with the colour of red, green, blue, and golden-brown, EVA encapsulation foils with red, yellow, green, blue, grey that come in different shades, special intermediate encapsulation foil that is manufactured by Solaxess, digitally ceramic printed front glasses with the colours of blue, red, yellow, white, and green that have different coverage ratio, and interference optic filters are investigated. Experimental researches have been completed by taking into consideration of possible commercial mass production; therefore, each material that has a potential to be designed as coloured PV systems were compared and tested as both visually and economically. Metal roofing colours that are commercially available in the housing market were also taken into consideration for visual appearances of each module and optimal colour matches were completed after lamination processes.

It is evident that, interference filters are way more expensive to be considered for a mass production. Conventional PV modules, having 0.66 €/Wp, that are laminated with mono-crystalline solar cells are half cheaper than PV modules that are laminated with coloured multi-crystalline solar cells which has 1.41 €/Wp. On the other hand, nominal output power of coloured solar cells is substantial and the visual appearance altogether satisfactory. Coloured EVA foils are economically the most feasible option; reaching less than 1.3 €/Wp for any colour option for EVA encapsulation. However, they fail to cover solar cells once it is laminated. Tempered glasses plainness is less than flat glass; hence bubbles may also occur during laminating it with EVA foil. Therefore, thicker EVA layers are necessary to overcome the possible bubbling and cracked cell problems. Overall, it is harder to manufacture one module by using coloured EVA encapsulators. Further investigation is necessary to make more optimal coloured EVA encapsulations for manufacturing PV modules; however, commercially, it is not applicable to manufacture coloured PV modules by choosing coloured EVA encapsulation as a coloured material option. By having 2.25 €/Wp, special intermediate foil that is designed by Solaxess makes the white PV module one of the most expensive design options for coloured BIPV systems. On the other hand, the colour blending is remarkable and solar cells are completely covered by the foil, making the PV module a great option for white roofs or façades. Cell-to-module loss is a major downside for Solaxess foil; it was seen that the nominal output power drops 47% of its initial value when Solaxess foil is used for PV module. Digitally ceramic printed front glasses give more design options for any innovative BIPV systems due to the possibility to print any kind of pattern or picture on the glass. The price for digitally ceramic printed glass is relatively higher than coloured solar cells and optimisation for coverage ratio is needed to yield optimal module efficiency with good visual appearance. In this work, it was clear that honey comb shaped pattern that has 98 % coverage ratio or hexagonal shaped pattern that has 84% coverage ratio have the best visual appearances Printing on the inner side of the front glass gave higher short circuit current values than the printing faced on the outer side of the front glass. In terms of colour short circuit current correlation ceramic printing that has white colour gave the highest current value among others, which is followed by red, grey, green, and blue. This comparison was observed under the same coverage ratio, 84%, however, current values are inconsistent with the colour and coverage ratio. Finally, the modules that are laminated with digitally ceramic printed front glass was found as follows: red module is 2.18 €/Wp, blue module is 2.64 €/Wp, green module is 2.5 €/Wp, and grey module is 2.4 €/Wp . The other patterns (dots, circles etc.) are needed to be investigated further with the same coverage ratio and further assessments are needed.

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