MASTER's THESIS – RENEWABLE ENERGY MANAGEMENT

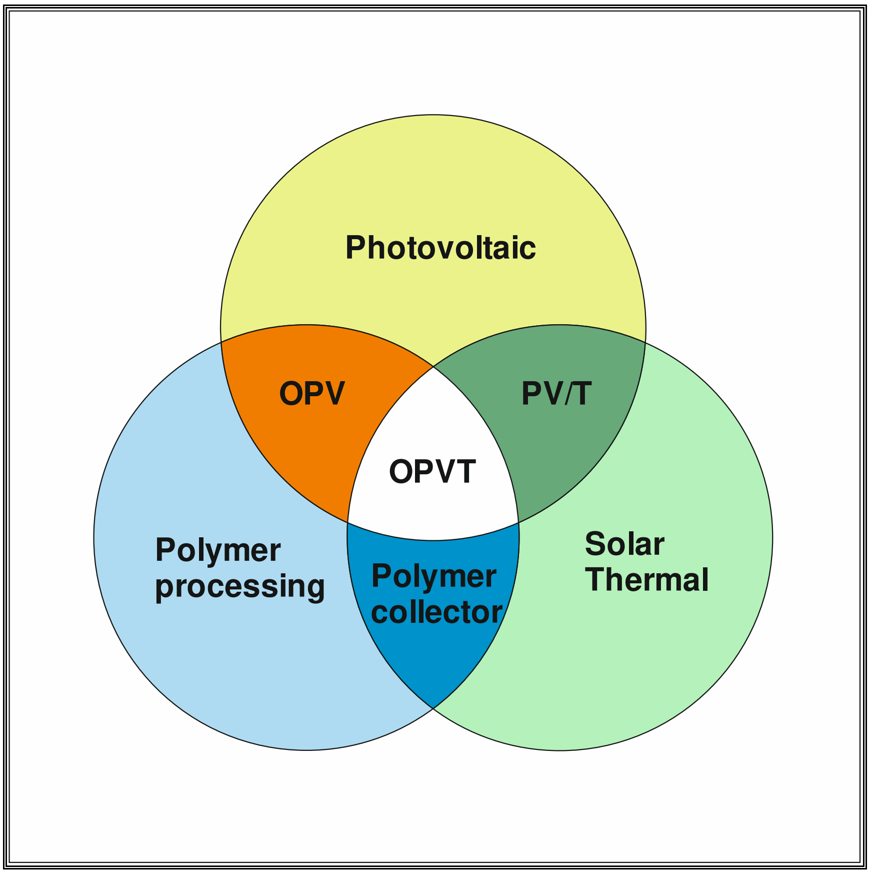
Cologne University of Applied Sciences – Institute for Technology and Resources

Management in the Tropics and Subtropics

and

Fraunhofer - Institute for Solar Energy Systems ISE

INVESTIGATION OF MARKET POTENTIAL OF POLYMER BASED PVT COLLECTOR



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In the Tropics and Subtropics

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Abbreviations

BMWi	German Federal Ministry of Economics and Energy
BoS	Balance of System
BS	Bus Station
CD	Crop Drying
COP21	Conference Of Parties 21
CPB	Car Parking Building
CV	Camping Vehicle
CWS	Car Washing Station
DHW	Domestic Hot Water
DIN	Deutsches Institut für Normung
ETC	Evacuated Tube Collector
FPC	Flat Plate Collector
ICS	Integrated Collector Storage
IEA	International Energy Agency
INDC	Intended Nationally Determined Contributions
ISE	Institute for Solar Energy Systems
OPV	Organic Photovoltaic
OPVT	Organische PV Module gekoppelt mit Thermiekollektoren
PA	Polyamide
PC	Polycarbonate
PE	Polyethylene
PEEK	Poly Ether Ether Ketone
PMMA	poly-methyl methacrylate
PP	Polypropylene
PPS	Polyphenylene Sulfide
PT	Toilet Booth
PVC	Poly vinyl chloride

PVT	Photovoltaic Thermal collector
R2R	Roll to Roll
SHC	Solar Heating and Cooling
TSS	Thermosiphon System
UV	Ultraviolet
UNFCCC	United Nations Framework Convention on Climate Change
WPC	Wood Polymer Composite

1. Abstract

For sustainable climate, an exponential growth in renewable heating and cooling is compulsory to reduce consumption of the fossil fuels for production of heat. An essential step from European Commission as an introduction of the strategy for renewable heat has given a platform to the solar thermal market to tap the highest possible potential. To grab the opportunity given, capacity of the production is to be increased as well as reduction in cost of solar thermal product is to be achieved by any suitable alternate means. Polymer based hybrid collector, named as OPVT collector, is the innovation from Fraunhofer Institute of Solar Energy Systems to break the road blocks for the solar thermal market. A polymer solar cell and a polymer solar thermal collector, both, technologies have tendency of high initial investments and extremely low running cost in business. The aims of this study were to develop a calculation tool for determination of production cost of different OPVT collector concepts and evaluate their potential with reference to market size. The tool was expected to be uniform for all possible concepts of OPVT collector and flexible in usage during the early stage of technological development. In this study, "Microsoft Excel" software based calculation tool is developed for estimation of production cost for different concepts. A Car washing station for water based OPVT collector and a bus station for air based OPVT collector are found be most suitable for start-up of the business. The analysis of results has highlighted that the minimum cost of OPVT collector can be referenced as its material cost. The OPVT collector business has huge potential and possibility of early break-even point in the production. As production costs are sensitive to material costs, input values to the tool must be accurate. Presence of dominance of the material cost is due to high cost of OPV. In industry, OPV is still being considered as the technological product instead the commodity product. This market potential study for OPVT collector technology has been the important step in giving the confidence to solar thermal, polymer and plastic processing industries for business investment.

Keywords – OPVT collector, production cost, calculation tool, market size

2. Introduction

2.1. Motivation

Globally, production of heat is accounted for about half of the final energy consumption. Fossil fuels fulfill 75% of that demand which is equal to one third of the global energy related CO_2 emissions. Decarbonization of such a huge emission through use of renewable energy was not in attention for most of the policy makers. However, there are certain signs of increasing consideration for renewable heat technologies after, so called – 'Paris Agreement' in the year 2015. Many countries have delivered numbers of INDCs to the UNFCCC for COP21 with the aim of expanding use and manufacturing of renewable heat technologies. In early 2016, European Commission launched first strategy which demonstrates growing awareness of the potential of renewable heating and cooling (OECD/IEA, 2016).

For solar thermal systems, an ambitious target like $1m^2$ of collector area for every European by 2020, equivalent to total capacity in operation of 320 GW_{th} and long-term potential of 1,200 GW_{th} represents market potential in the European Union (ESTIF, 2007). In the fragmented nature of solar thermal market, it is apparent that rapid growth in production requires for solar thermal technologies. In addition, fast integration of solar thermal into buildings, exploration of new application and market segments are equally important to meet the targets. It is worth to mention that there is a high competition due to low price of fossil fuel and other renewables. This directs not only to increase the production capacity but also look for some alternative ways to achieve this.

At Fraunhofer Institute of Solar Energy Systems (ISE), this has been addressed in two steps after extensive research in a distinctive and an innovative way. In the first step, the use of alternate material as polymer and novel designs for solar thermal system in polymer has been presented through the Task 39 of the solar heating and cooling program (SHC) established by International Energy Agency (IEA). This has addressed issues like mass production possibilities, cost and weight reduction potential and freedom in new design for solar thermal systems. Next step, of course, leads to the direction of market penetration which is challenging. An innovative way, as synergy of two technologies, is the second step to reach to the different market segments with reliable, economical and most ecological products of solar thermal systems.

Synergy of two technologies means integration of organic photovoltaic and polymer based solar thermal collector. Organic photovoltaic, also known as polymer cell has excellent advantages like – flexibility in structure and dimension, thin and lightweight, transparent, positive temperature co-efficient at medium temperature. However, organic photovoltaic has limitations on efficiency and life. The benefits of the organic photovoltaic are most promising for integration into the polymer based solar thermal collector.

The combination of both the technologies will result into new product for solar thermal market, named as "*Organische PV Module gekoppelt mit Thermiekollektoren*" (OPVT) in the project. This project is funded by BMWi and cooperation from several relevant industrial partners. Objective of the OPVT project with BMWi and industrial partners is to evaluate the possibilities of the technology and identify the possible applications and concepts based on the economic evaluation. Organic photovoltaic and polymer solar thermal collector, both, are technologically available products but commercially yet to get exploit. Both the businesses have common characteristics of high capital investment and low running cost which demands large market volume for earlier positive revenue. Due to these business characteristics, it is important to make investigation of market potential at the start of the project. With this motivation, research has been made through this thesis. This challenge has been evaluated on two fronts for OPVT collector – one by defining the production cost and second by estimating the market size for most promising applications and concepts.

2.2. Objective

The aim of this master thesis is to develop a calculation tool for the determination of production cost for different concepts of OPVT collector and evaluate them based on these results, the potential of a given concept regarding market size, production volume and costs. With such a tool, OPVT collector designs should be evaluated at the design stage without further technological development which is important for the project objective and the involved partners. As many factors are to be estimated for the selected concepts, parameter variation should be performed to study the sensitivity of the tool to certain inputs.

A uniform tool capable of calculating different plausible concepts specified for the evaluation of different applications, different production technologies, market sizes, different materials has to be developed.

The application scenarios should reflect the positive potential of OPVT collector in terms of standardization, simplification, ease in integration, manufacturability and minimum initial investment.

Development of production cost calculation tool should be done in such a way that production cost for any possible concept of OPVT collector can be estimated at the feasibility stage and tool's output should have a comparable unit like €/m^2 or €/module.

With the appropriate methods of data collection, input data is to be fed into the tool for getting the production cost range results for each concept. While performing the cost analysis, it should give information about which concept is promising for prototyping and commercialization. Most influencing parameters should be identified from the tool, which need detailed input.

3. Theoretical Framework

In this chapter, first, trend in the solar thermal installation, major solar thermal technologies and their market forecast by several experts has been studied. Subsequently, technical characteristics and possible application areas are studied for solar thermal technologies. From these two studies, a direction for market segments for OPVT collector and focus on types of collector technology has been defined. Later, technical features, market position and future direction for PVT collector have been studied. Requirement of the proven product and low cost for hybrid collector have been concluded from the studies for PVT collector. A comprehensive study on polymer based solar thermal collector for material, manufacturing processes, and state-of art products and concepts have been conducted. Similar studies have been also performed for OPV. The studies on, both, polymer solar thermal collector and OPV have been useful in defining the possible capabilities of OPVT collector which is useful for assessment of market segments. In addition, product characteristics, manufacturing constraints and capability of products are noted which is useful in defining the concepts for OPVT collector. Different methods of production cost calculation and their business relevance are studied which has given insight on cost types to be considered for calculation of the production cost for OPVT collector. Various business models for cost accountability of the product has been studied and figured out about possible business model for OPVT collector business. In the last, all possible methods for market potential estimation for the global market has been studied extensively which has given an analytical direction for estimation of market potential for promising applications of OPVT collector.

3.1 Solar thermal market

In last decade, globally, solar thermal capacity has been increased by four-fold (REN21, 2017). By the end of 2016, the total solar thermal capacity is approximately 456 GW_{th} as shown in the Figure 1. In the year 2016, China added nearly 27 GW_{th} which is accounted for 75% of the total global capacity. Other countries in the top five lists are Turkey, Brazil, India and the United States of America. The capacity addition in the year 2016 by major countries is represented in the Figure 2. Increasing interest from several emerging markets like Eastern and Central Africa, Middle East shows the globalization of the solar thermal market. Despite 8% reduction in new installation in 2016, Germany has installed 0.74 million m^2 of solar thermal collector area which is equal to 521 MW_{th} capacity. The cumulative solar thermal capacity for Germany is approximately 13.9 GW_{th} by the end of 2016 (IEA-SHC, 2017).

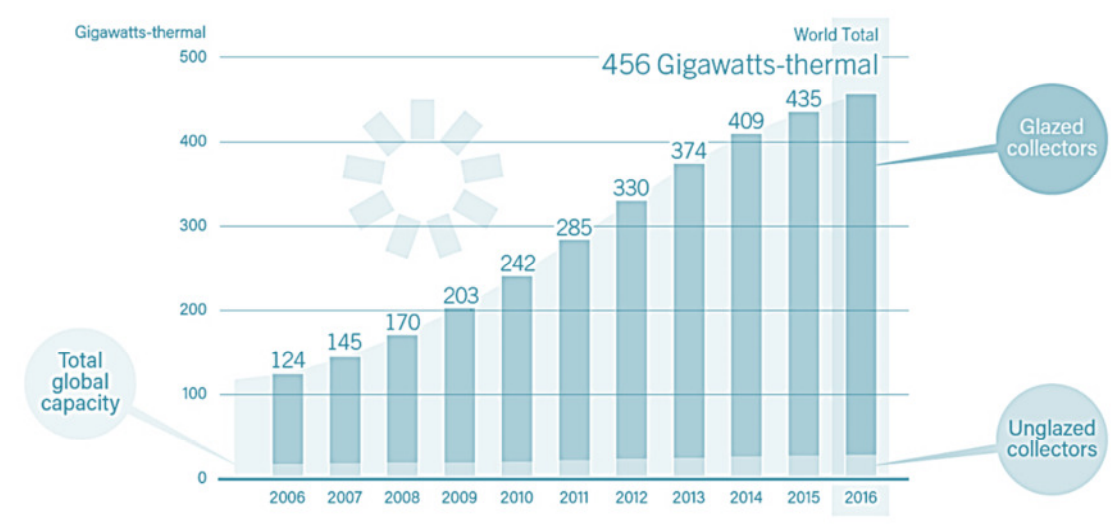


Figure 1 Global cumulative solar thermal capacity from 2006 to 2016 (REN21, 2017)

Glazed collectors are dominating the global market over unglazed collectors. The distribution of collector types for the worldwide capacity in operation by end of 2014 was approximately 71% evacuated tube collectors (ETC), 22% flat plate collector (FPC), 6% unglazed collector and 1% glazed and unglazed air collectors as shown in Figure 3. Within the glazed collectors, there has been an inhomogeneity between flat plate collectors (FPC) and evacuated tube collectors (ETC) between different regional markets. In China, the major market is dominated by the evacuated tube collectors whereas the flat plate collectors are dominating type for the European market. In Germany, approximately 90% of the collector market is dominated by the flat plate collectors (INTEC, 2016).

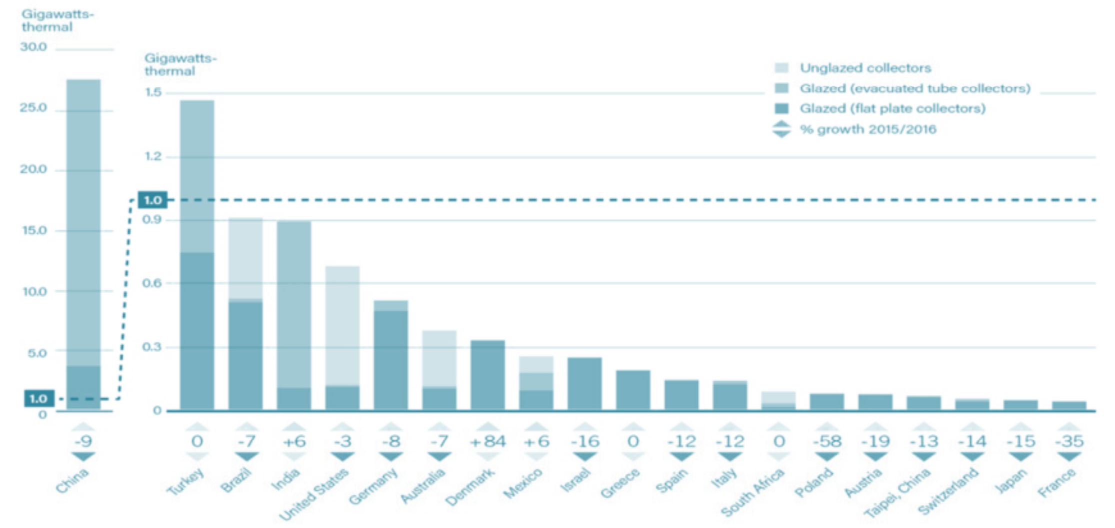


Figure 2 Solar thermal capacity additions in year 2016 by top 20 countries (REN21, 2017)

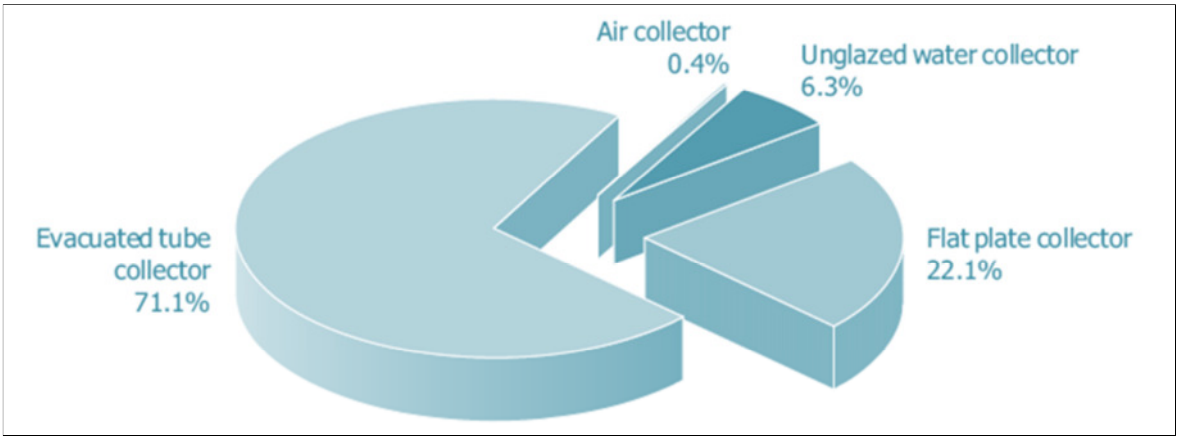


Figure 3 Distribution of total installed capacity by collector type in 2014 – Global (INTEC, 2016)

Regardless of decreasing trend in solar thermal installation for the last three years, the German government has framed many ambitious goals in the "*Energiewende*" (energy turnaround) for promoting the solar heat market. In the German Solar Heating Roadmap, 8% share of solar heating for the households and 10% share of solar fraction for the German industry is intended (IEA-SHC, 2017).

Future of the global solar thermal market depends on many factors such as change in oil and gas prices, reduction in the fragmented nature of the solar thermal market, policy support mechanism from respective governments and so on. By Sarasin 2011, 12% of average annual growth is expected for the global market until 2020 which will result into 186 GW_{th} of new capacity addition in the solar thermal market. After 2020, a steady growth is expected. To meet this expected growth, a change in the share of solar thermal technologies is predicted. The technological development such as polymer collectors and hybrid collectors are expected to contribute to these changes (Michael Köhl, 2012).

3.2 Solar thermal applications

A wide range of applications are offered by solar thermal energy for heat production. All the applications are mainly driven by the level of temperature required. A low temperature heat (<250˚C) potential is mostly suitable to solar thermal energy. For Germany, 35% of the final energy demand is used in applications below 100˚C (IEA-SHC, 2017). Based on the temperature requirement, collector technologies vary from modest one to the most sophisticated product. Seven different applications are illustrated in the Figure 4 with the temperature range categorization.

Swimming pool heating by solar energy is the simplest solar thermal application in which unglazed collectors are mostly used. The unglazed collector work at atmospheric pressure and does not require thermal storage as pool acts as the thermal storage. In general, 1 m^2 of collector is used per m^2 of the swimming pool in the European countries (Michael Köhl, 2012).

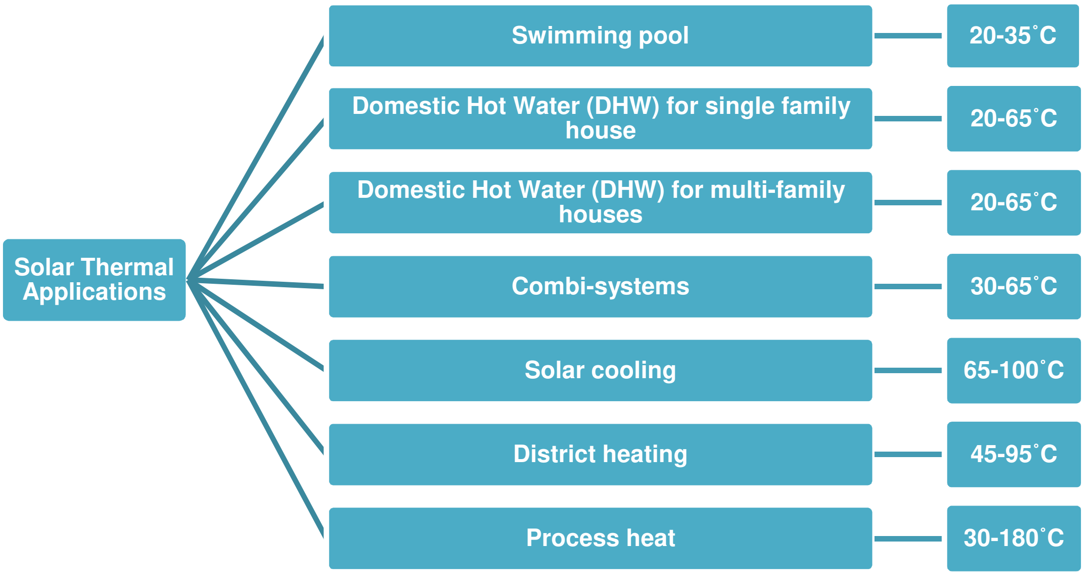


Figure 4 Solar thermal applications with respective temperature level (Michael Köhl, 2012)

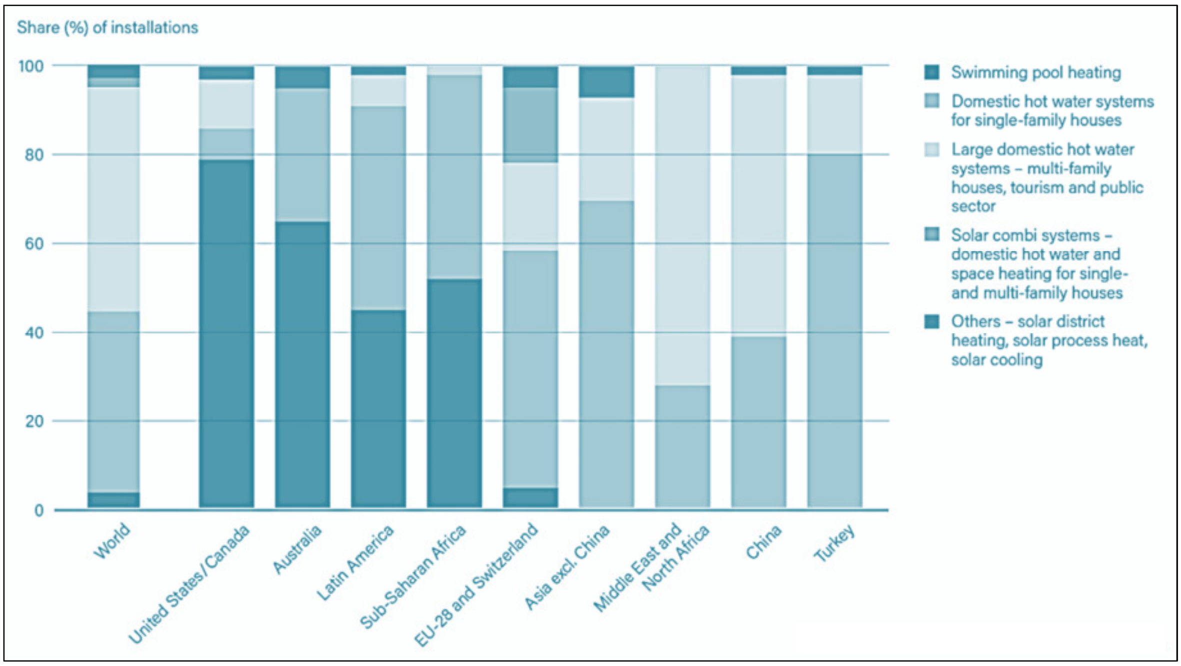


Figure 5 Share of newly installed capacity of solar thermal applications by Economic Region, 2015 (REN21, 2017)

Share of solar water heater applications for different region is represented in the Figure 5. The swimming pool absorbers are widely used in the United State of America, Canada, Europe, Australia and Sub-Saharan Africa. The European countries are quite balanced in usage of the solar thermal applications. The Solar district heating, process heating and solar cooling applications are at the demonstration level, where economic market development is on limited scale (Michael Köhl, 2012).

For Germany, the most suitable applications are small space heating and domestic hot water for one- and two-family houses. Approximately 30% of new installed systems are for space heating system and 70% for DHW (IEA-SHC, 2017). In recent years, there has been increased focus on solar district heating system and industrial process heat and several demonstration projects of such systems are installed at different locations of Germany. The German Federal Ministry of Economics and Energy (BMWi) is responsible for coordination of the solar thermal energy research in Germany (IEA-SHC, 2017). BMWi has defined four strategies for capturing the full potential of the solar thermal technologies. They are described as sharp increase of numbers of solar thermal systems, progressive increased share of solar thermal energy per building, introduction to new market segments like public buildings and commercial sector and development of new solar thermal applications (Israel, 2012).

3.3 Solar thermal technologies

A thermal performance of the solar thermal applications largely depends on the solar thermal collectors. The basic function of the solar thermal collector is to absorb the solar radiation from the sun and to convert it into heat to the fluid with the highest possible efficiency. The absorber, main component of the collector, must be designed with high absorption capacity in the solar spectrum and low emission capacity in the heat radiation spectrum. Moreover, heat loss to the ambient in the collector is limited by using transparent cover in front of and thermal insulation underneath the absorber.

There are three main types of the technologies of the solar thermal collectors are available in the market based on use of thermal energy, temperature level and costs. They are – unglazed collectors, flat plate collectors (FPC) and evacuated tube collectors (ETC). The efficiency of these collectors is calculated as calculated as per below equation (Michael Köhl, 2012).

$$\eta = \eta_0 - \frac{a_1(T_m - T_a)}{G} - a_2 G\left(\frac{T_m - T_a}{G}\right)^2$$

Where:

η_0 is the optical efficiency (-);

a_1 is the heat loss coefficient (W m^{-2} K^{-1});

a_2 is the temperature dependence of the heat loss coefficient (W m^{-2} K^{-2});

T_m is the mean temperature of the fluid in the absorber plate (K);

T_a is the ambient temperature (K);

G is the solar irradiance on the collector plane (W m^{-2})

The efficiency curve can be drawn based on the coefficients optical efficiency (η_0) and the reduction coefficients (a_1, a_2) which is represented in the Figure 6 for all three types of the collectors.

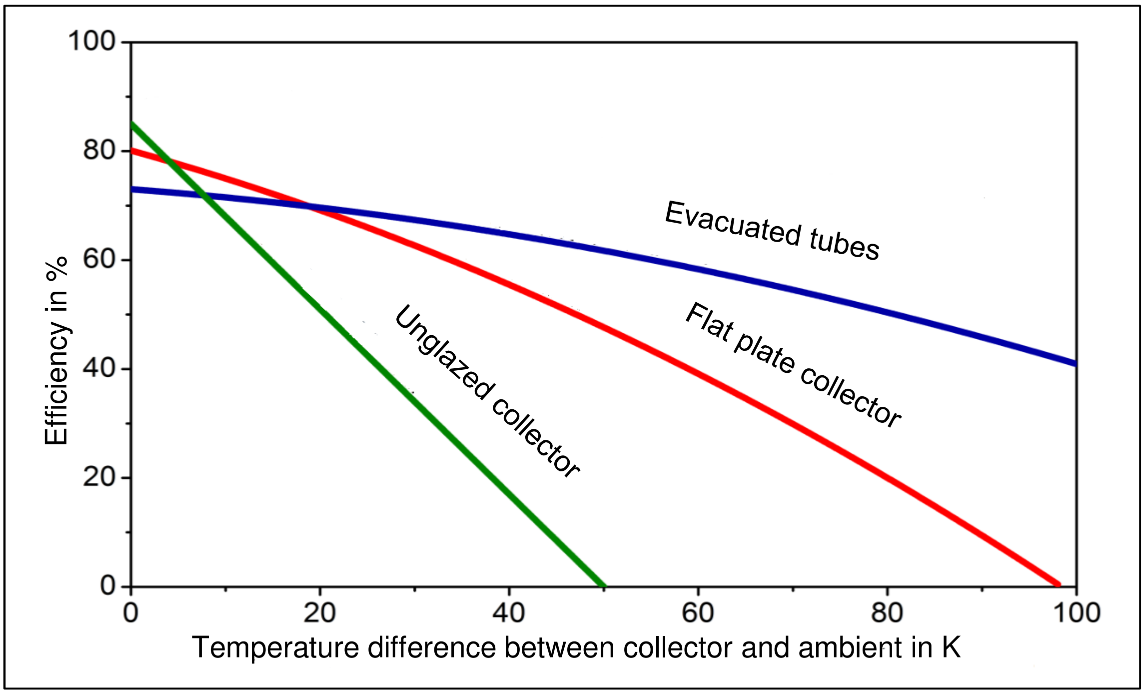


Figure 6 Efficiency characteristics of the different collectors as a function of the temperature difference (Peglow, 2014)

3.4 PVT solar thermal collector

Hybrid photovoltaic-thermal (PVT) collectors produce heat and electricity simultaneously in one module. The basic idea of the concept is to utilize more of the solar radiation by also harvesting the waste heat that is generated in photovoltaic (PV) modules. This is achieved when PV panel or laminate, which convert solar radiation into electricity, also functions as the absorber of a thermal collector. The materials used for PV cells are mostly very sensitive to temperature. If the temperature increases, the electrical efficiency will drop. However, if the thermal energy that causes the increment in temperature in solar cells is removed and used in way that it prevents the temperature increase in PV cells and increases the overall efficiency of the system at the same time.

Other claimed benefits of PVT systems are that they require less space than separate solar thermal and PV systems, and can provide a more uniform architectural appearance (Clara Good, 2015). The design and integration of PVT into the rest of the building energy system is therefore of high importance to reach good efficiencies. So far, covered PVT collectors are relatively rare in the market. A large majority, around 80%, are uncovered PVT collectors. Even though the PV and solar thermal markets are both dominated by Chinese companies, most of the PVT producers are from European countries. In the Task 35 for PVT collectors, a market survey has pointed economic benefits and the possibility of building integration as the two most important factors. However, PVT systems are rarely or never reported to be cheaper than alternative installations (Clara Good, 2015).

Researcher believes that photovoltaic has been dominated by solid state junction devices, often made of silicon. However, this dominance is now being challenged by the emergence of a new generation of photovoltaic cells, based on for example, nano-crystalline materials and conducting polymer films which have attractive features like cheap fabrication and high flexibility. Photo-electrochemical systems can be produced more cheaply and at less cost in energy than silicon cells for which approximately 5 GJ is spent to make 1 m^2 of collector area. Unlike silicon, their efficiency increases with temperature, narrowing the efficiency gap under normal operating conditions (Kamran Moradi, 2013).

3.5 Polymer based solar thermal collectors

The intention behind the development of polymeric solar water heating systems is to reduce the cost of solar system substantially and thereby increasing market penetration. Cost and weight reduction are possible by using less expensive and lighter weight polymeric components. A weight reduction can also lead to reduced logistics and installation costs. In this chapter, overview on polymeric material used in the solar thermal applications, polymer manufacturing processes, state of the art – polymeric materials in solar thermal collectors are described.

3.5.1 Polymers – Overview for solar thermal energy

Polymer materials for solar thermal components pose several critical adjustments between material properties, process ability and cost. With the current state of technology, thermoplastic materials are widely used. There are three classifications of the thermoplastics based on their properties and market share. They are – standard thermoplastics, engineering thermoplastics and high-performance thermoplastics. Classification of the thermoplastic materials with reference to service temperature, structure and cost is shown in the Figure 7. The standard thermoplastics are lowest in cost as well as in service temperature (<100˚C) but accounts for 90% of the market share. Materials like polyethylene (PE), polypropylene (PP), polyvinyl chloride (PVC) are the standard thermoplastic materials. Engineering thermoplastics are having service temperature range between 100˚C and 150˚C. Polycarbonate (PC) and polyamide (PA) are the common engineering thermoplastic materials. High performance plastics have service temperature higher than 150˚C and the common materials are polyphenylene sulfide (PPS) and poly ether ether ketone (PEEK). The engineering plastics and high-performance plastic are accounted for remaining 10% of the market share (Michael Köhl, 2012).

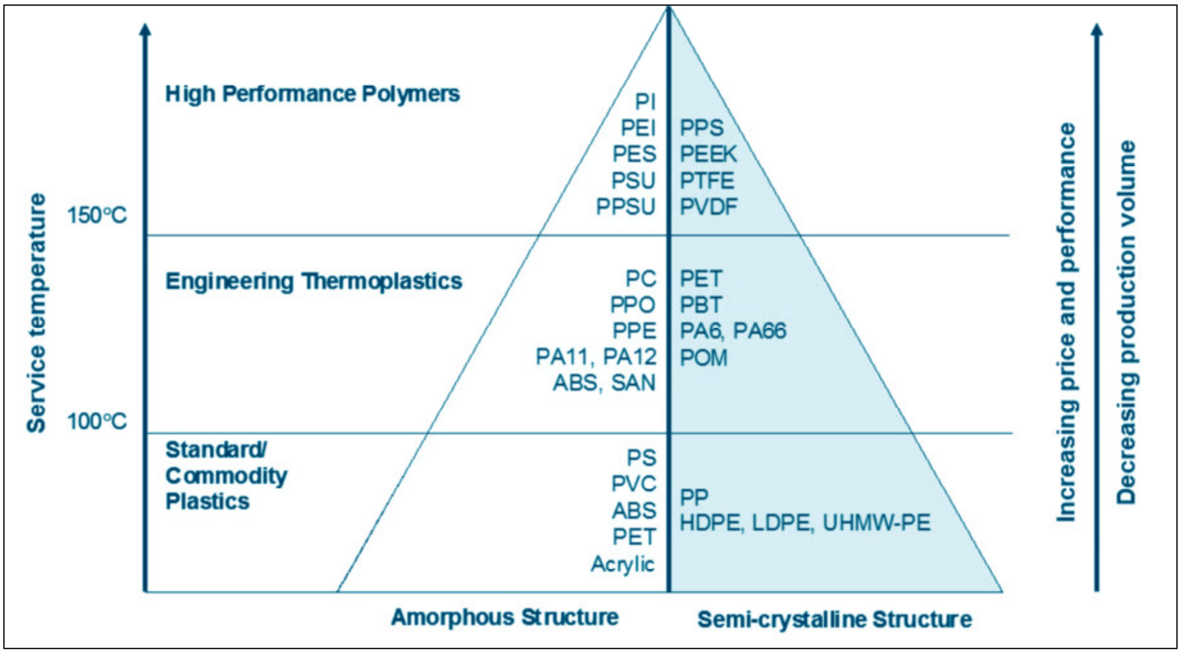


Figure 7 Classification of thermoplastic materials by service temperature, structure and cost (Michael Köhl, 2012)

The desired properties for polymer glazing materials are – high transmittance across the solar spectrum, resistance to degradation related with UV exposure and high temperatures, and impact resistance. Degradation of the transparent polymer glazing results into yellowing. Due to lower surface hardness of polymer compared with glass, an anti-scratch coating is highly recommended for polymer glazing. Polycarbonate (PC) and poly-methyl methacrylate (PMMA) are the possible polymer grades for the glazing applications (Michael Köhl, 2012).

Polymers offer excellent corrosion resistance, reduced weight and integration with other polymer components. In addition to these, polymeric absorbers need to have properties like compatibility with potable hot water and an anti-freeze, stable properties over operating temperature range, and good long term mechanical performance at high temperatures. Depending on the collector design, polymeric absorbers may be required to be UV resistant. The possible polymer grades suitable for absorber are PPS, PPO and PPA. The constraint of lower thermal conductivity for polymer (0.15 - 0.5 $W m^{-1} K^{-1}$) compared with steel (50 $W m^{-1} K^{-1}$) must be considered while design of the absorber (Michael Köhl, 2012).

Polymer material for housing can help to reduce the thickness of the insulation because of lower thermal conductivity. High insulation at low weight is possible to achieve with foamed plastics such as open-cell melamine foam. Use of insulation as structural element enhances the stiffness of the solar thermal collector (Michael Köhl, 2012).

In Task 39, the alternate material for mounting and framing elements as wood polymer composite (WPC) is found to be promising for solar thermal collectors. WPC materials are cost-efficient and environment-friendly construction elements. It contains 65% of wood and 35% PP and additives. Profile extrusion and injection molding are typical manufacturing processes for WPC materials (Michael Köhl, 2014).

3.5.2 Polymer manufacturing processes

In polymer processing, a distinction is made between primary forming, cutting and joining processes (Peglow, 2014). In primary molding process, products are formed by melting of raw material and subsequently shaping them. Polymer cutting is achieved by milling and sawing. There are three main polymer forming processes are described in this thesis. They are – extrusion, injection molding, and thermoforming.

Extrusion is a continuous pre-forming process in which granular or powdery plastics are melted and brought into the defined shape by applying pressure through a nozzle. Depending on the nozzle, various shapes such as profiles, tubes, sheets can be produced. Profile extrusion, blow molding, co-extrusion are interesting extrusion processes suitable for the solar thermal components like glazing and absorbers. The profile extrusion allows manufacturing of hollow profiles like twin-wall or multi-wall profiles. Sometimes, properties of one material are not sufficient for the application. Co-extrusion process allows use of two different polymer materials to meet the demand of application. Melt of the materials are divided by displacer bodies and combined in the compression zone with the desired cross section of the profile. In the blow molding extrusion process, the extruded tubes are made from a polymer melt, formed directly after leaving the die. In injection blow molding, injection molded pre-form is reheated to the blowing temperature and blown into shape by air pressure (Peglow, 2014).

Injection molding process principle is to inject a polymer melt into a closed mold cavity where solidification happens under pressure. The mold is opened after cooling time to release the part from the mold. Parts with high dimensional stability can be produced through injection molding process (Peglow, 2014). The process time is longer than extrusion process and the parts are costly when produced with injection molding process. End caps and headers in the solar thermal collectors are the product examples from this process.

In thermoforming, an extruded sheet or polymer plate is heated in an entropy-elastic state that is between the glass transition and melting range. The heated preform is deformed by a shaping force into a mold where it cools. The most used technique for deforming the preform depends on reduction of pressure on one side to allow atmospheric pressure to deform it on the other side (Peglow, 2014). An important benefit of the vacuum forming is the possibility to mold large parts. Housings are most common products produced from thermoforming process.

Polymer joining is possible by either welding or bonding of two polymer parts. It is important to note that only thermoplastics are possible to weld. According to DIN 1910, following methods are possible for welding of plastics (Peglow, 2014). They are – heating element welding, hot gas welding, infrared welding, ultrasonic welding, friction welding and high frequency welding. The welding processes are mainly divided into two categories. One is supply of energy from outside for melting and second is energy introduced by friction. Except friction welding, all other welding methods described above belong to category one. The selection of proper welding method depends on material used, geometry to be welded, requirement of strength, cycle time and investment costs. High frequency welding is used for welding of plastic films. Ultrasonic welding cannot be used for joining of PP. For welding of extruded profiles or tubes, the heating element welding is widely used. The heating element (a Teflon coated aluminum plate with heating rods) heats the surfaces of the components to be welding temperature and press them against the heating element. During heating period, polymer material is plasticized. The connecting surfaces are welded under pressure once the heating element is removed. Investment cost of such welding method is very low. Infrared welding is the non-contact joining process. The parts are heated without contact by means of infrared radiation and are joined under pressure. Infrared welding is used when joining of two joining parts are with different melting temperatures (Peglow, 2014).

Bonding is achieved by applying an adhesive to the joining materials. An adhesive is the non-metallic substance that can join two parts by surface adhesion and internal strength. An important point when bonding plastics is the polarity of the plastics resulting from the molecular structure. To obtain suitable polarity, the surfaces which have lower surface energy are to be treated by suitable surface treatment method. PP material is having low surface energy and is only to be bonded with the aid of costly pretreatment methods (Peglow, 2014).

3.5.3 State of the art – polymeric materials in solar thermal collectors

In this chapter, some of the products and concepts of polymer based solar thermal collectors emerged outside or within the framework of IEA-SHC Task 39 activities are explained which are relevant in defining concepts for the OPVT collector.

3.5.3.1 Pool absorber

Magen eco-Energy is an expert in an innovative Over-Molding Injection technology. This technology enables the manufacture of seamless, leak-proof and integrally-molded thermoplastics. *Magen eco-Energy produces* three types of solar thermal collectors: 1) Helicoil; 2) eco-Flare; and 3) eco-SPARK. Out of three products, eco-SPARK is described and shown in the Figure 8. It is full plastic glazed panel for swimming pool heating, made for the cooler and windy regions. It also fulfills the demand of higher water temperature for the swimming pool. The absorber is made from specially formulated polypropylene (PP) material which enables high pressure/temperature creep resistance.

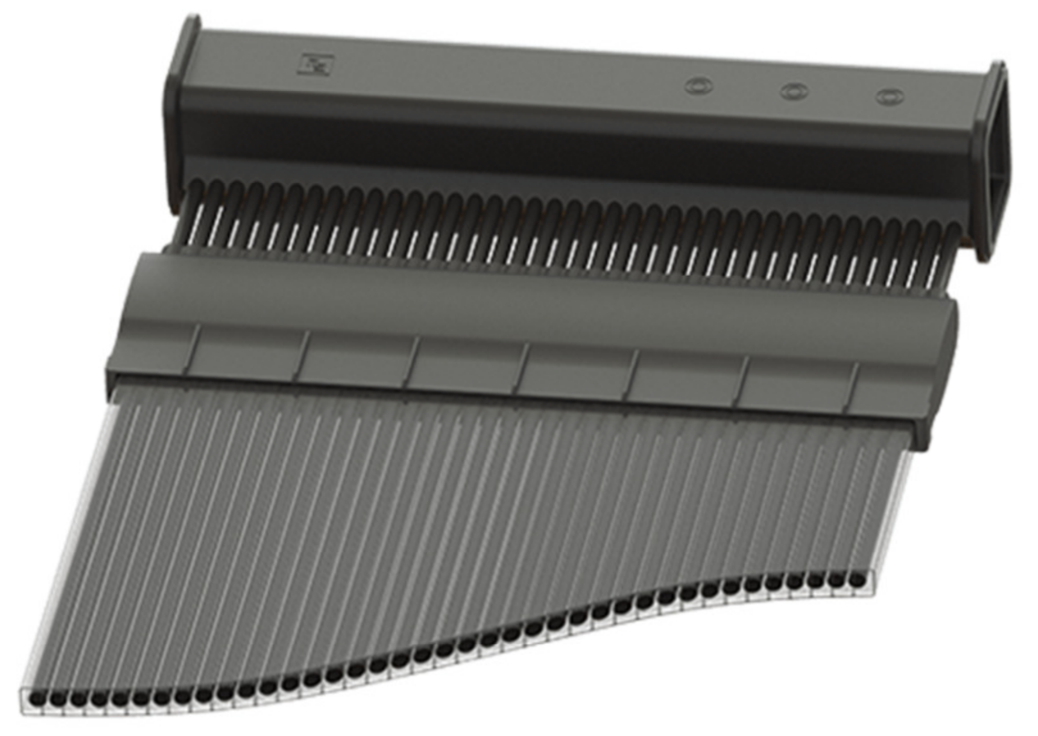


Figure 8 Pool absorber (eco-SPARK) produced by Magen eco-Energy (Magen, 2017)

A large number of extruded tubes are connected in parallel with manifold headers by special injection-over molding technique. This process is fully automatic and able to produce 500 x 4 m^2 absorbers. The glazing is made from polycarbonate (PC). It produces the greenhouse effect around each tube which helps in improvement of thermal efficiency significantly. Stagnation temperature of the collector is defined as 150°C. The design of this fully polymeric collector is corrosion resistant, anti-scaling and capable to withstand vandalism and moderate subzero temperatures. An important aspect of lifetime guarantee as 10 years is the scope for improvement defined for absorber material by *Magen eco-Energy* (Michael Köhl, 2012).

3.5.3.2 Glazed flat plate collectors with polymer absorber

Aventa AS has developed solar collector absorber of polymer material with the aim of providing the product which can withstand temperature and other impacts due to climate without providing the application of overheat protection features. Only high-performance polymer can withstand the extreme temperatures that may occur during the stagnation conditions in the solar thermal collectors. This has been taken care while deciding material for the absorber. The modules have fixed width of 0.6 m and possible to produce in various lengths up to 6 m. A cover is made of twin-wall polycarbonate (PC) sheet and absorber is made of polyphenylene sulfide (PPS). The thickness of the collector is 60 mm in which 25 mm is the thickness of insulation. The dry weight of the collector is 5 kg m^{-2}. Figure 9 shows the cross-sectional model of the collector from Aventa (Michael Köhl, 2012).

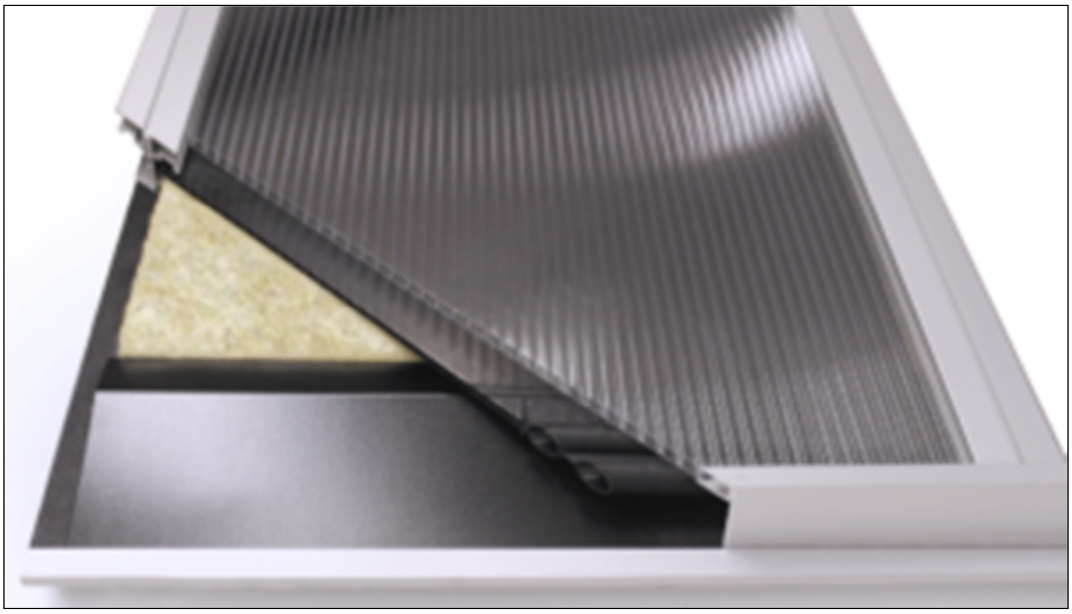


Figure 9 Cross-sectional model of polymer flat plate collector from Aventa AS (Aventa Solar, 2017)

The absorber module is an extruded sheet with internal rectangle channels. The ends of the absorbers are mounted with endcaps and joined by infrared welding process. Aventa has successfully achieved welding of thin wall thickness, large dimensions, and having different material properties. The collector uses pure water as the heat carrier. The main flow in the absorber sheet is in upward direction and only the one out of 55 parallel channels is used for flow back to the manifold outlet pipe. The collectors are possible to couple in parallel. The thickness of the absorber wall is kept in order of 1 mm for effective heat transfer and good performance of the absorber. The collector is tested for durability and it revealed that the collector is able to operate in the warmest European climate for at least 20 years without damage. The stagnation temperature of the collector is kept below 160°C. For prevention of collector from freezing and boiling, the drain-back system is used (Michael Köhl, 2012).

3.5.3.3 Air collector systems

Enerconcept, a Canadian company, has developed polymer based space heating solution. The Lubi^{TM} air heater wall with 80% efficiency is suitable for all solar heating applications (Michael Köhl, 2014). It uses UV treated polycarbonate (PC) and patented perforated glazing technology. Its air flow is lower than 100 $m^3\ h^{-1}\ m^{-2}$ and shows temperature increase of 45 K above the ambient temperature (Michael Köhl, 2014). The air collector is mounted either on façade or roof with adequate tilted angle for the high function output. Figure 10 shows the Lubi^{TM} air heater wall piece exhibited during Task 39.

Figure 10 Lubi^{TM} air heater wall piece exhibited during Task 39 (Michael Köhl, 2014)

3.5.3.4 Integrated storage collector and thermosiphon systems

Integrated storage collector and thermosiphon systems are typically designed for climates without freezing during the winter. Storage is the collector in case of integrated storage collector whereas storage is close to the collector for thermosiphon systems. Further detailing is done only for thermosiphon system.

Aventa has developed a novel concept of polymeric thermosiphon system. It uses absorber made from polypropylene (PP) material. The absorber has the channel structure in extruded twin-wall sheets which enables minimum flow resistance in a flow circuit. (John Rekstad, 2015) Figure 11 shows the design of the thermosiphon system from Aventa. A storage tank is welded to the top end of the absorber. The bottom of the absorber is welded to the endcaps. The collector area is approximately 1 m^2. The circulation of the heat carrier takes place within absorber channel. Cold water flows down in the outer channels from bottom of the storage tank, and rises in the central channels when heated by the solar irradiation as shown in Figure 12. Stratification inside the storage tank enables the water circulation.

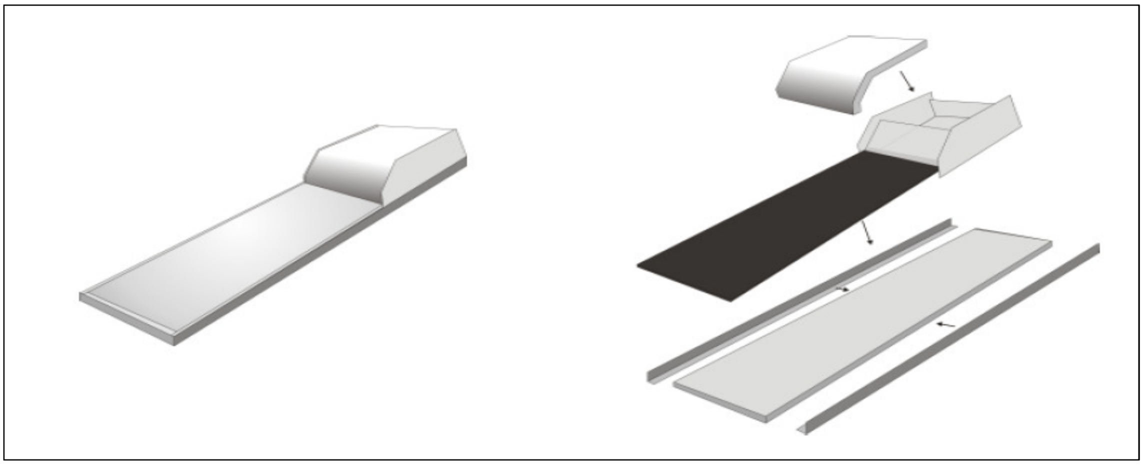


Figure 11 Polymer based thermosiphon system from Aventa AS (John Rekstad, 2015)

During night, absorber cools down and both the channels are exposed to the same cooling effect. This prevents inverse circulation of the water and tapping of heat from the storage tank. A thermosiphon system prefers low pressure due to use of polymeric material, which means that the boiling temperature in the system is close to 100°C. Hence, it is necessary to maintain system temperature below this threshold which indicates the overheating protection as the crucial point of the design.

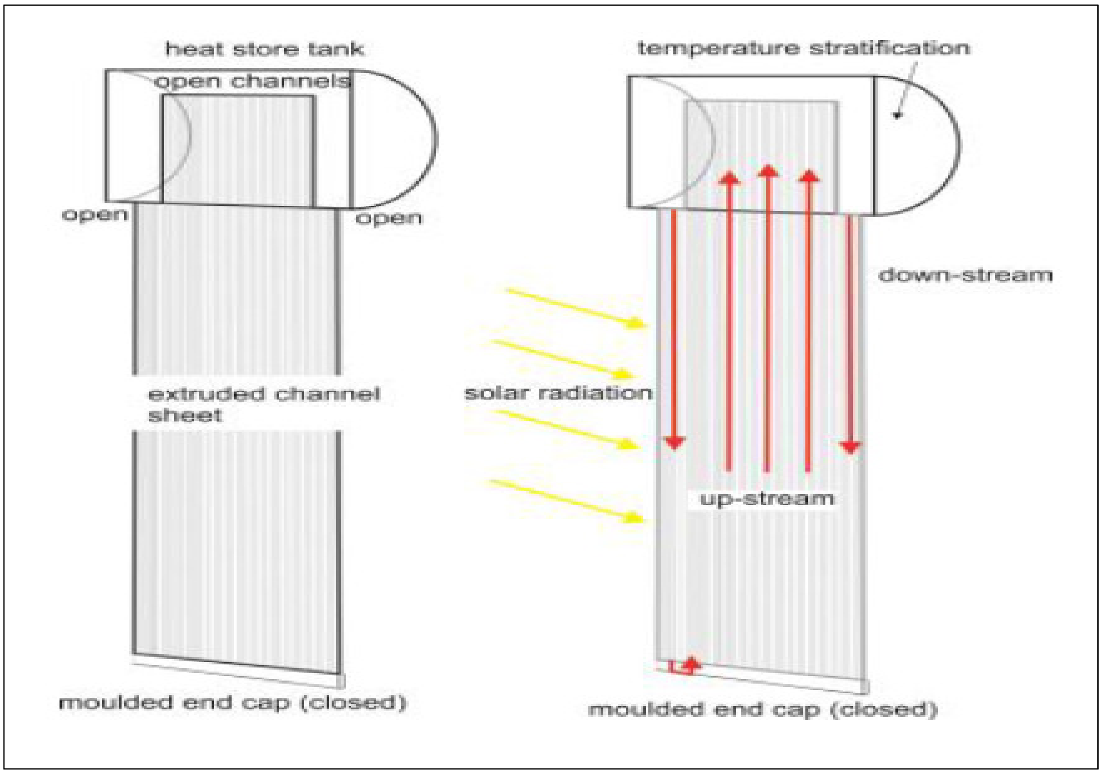


Figure 12 Water flow in absorber channel in thermosiphon system from Aventa AS (John Rekstad, 2015)

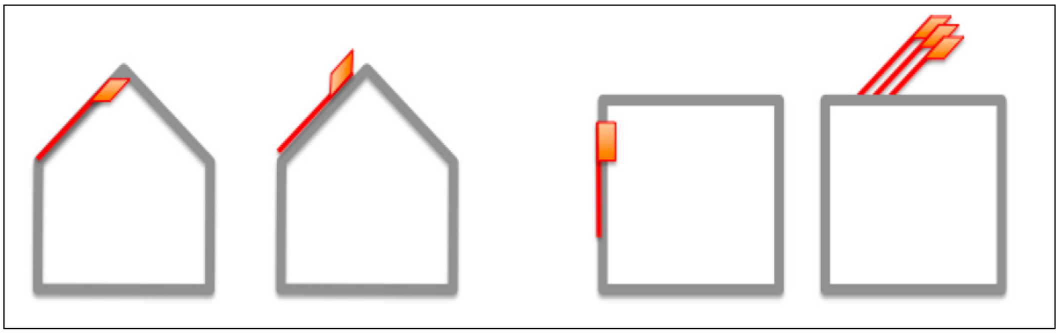


Figure 13 Possible mounting positions with Aventa thermosiphon system (John Rekstad, 2015)

While designing the thermosiphon system, Aventa has considered several installation modes which are roof or façade integration with the storage tank on the backside of the system, a roof top or vertical installation with the storage tank on the top side or behind of the absorber sheet as shown in the Figure 13.

3.6 Organic photovoltaic cell

3.6.1 Construction and operating principle

Silicon solar cell uses inorganic materials for the conversion of solar irradiation to electricity whereas OPV cell uses organic polymers as semiconductors. It has both advantages and disadvantages. Extremely poor charge-carrier mobility is the most important disadvantage of the organic semiconductors when compared to their inorganic counterparts. On the other side, they possess stronger absorption coefficient which makes it possible to have very thin layers and thereby reduce material consumption and costs (Özbilgin, 2016).

In the structure of OPV cell, it makes use of an active layer where the conversion of light into electricity takes place in between two electrodes. The polymer active layer is comprised of a mixture of a donor and an acceptor material, which is referred to as a bulk-heterojunction. This allows for a large donor-acceptor interface area, which helps electron-hole pairs (excitons) with low mobility to reach to interface and disengage.

Figure 14 displays the two most common geometries for OPVs, which are normal and inverted geometries, built up of Poly (3-hexylthiophene-2.5-diyl) (P3HT) and Phenyl-C61-butyric acid methyl ester (PCBM) in the active layer.

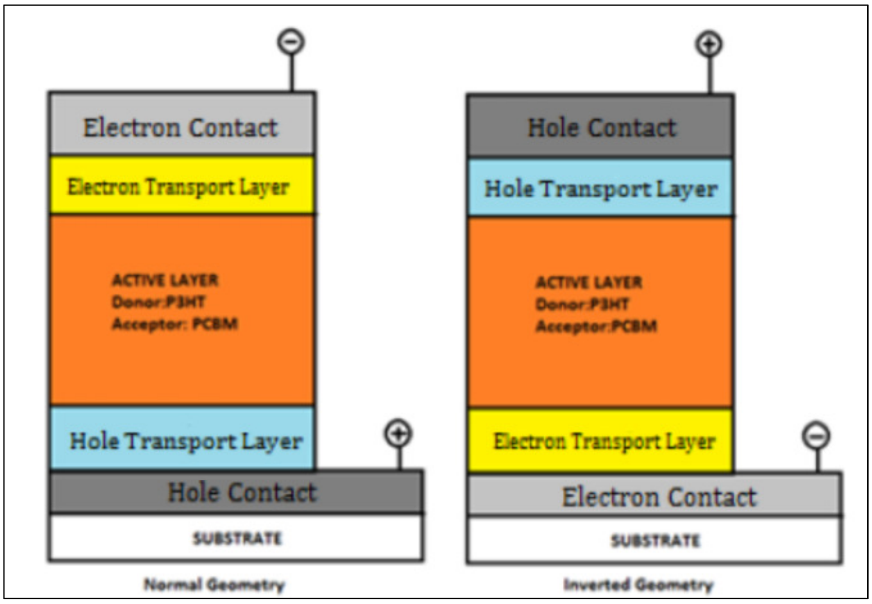


Figure 14 Normal (left) and inverted (right) geometry of OPV cell (Özbilgin, 2016)

The mechanism of transforming light into electric current starts with the absorption of a photon, which leads to creation of an exciton. The exciton then must reach the donor-acceptor interface with a difference in ionization potential large enough to overcome the binding energy, to separate into free charges. When the ionization potential difference is large enough, the resulting free charges can then travel through either the electron or the hole transfer layer and be collected at the electrodes and thus generating electricity.

The inverted geometry is preferred over the normal geometry because it reveals better stability and longer lifetimes by avoiding a low work-function metal cathode. Instead, air-stable metals are used as the top electrode which allows the device a better self-encapsulation (Özbilgin, 2016).

3.6.2 Roll-to roll manufacturing of OPV cells

One of the biggest advantages of OPV cells is that they can be manufactured by roll-to roll (R2R) coating, printing, sputtering, patterning and lamination machinery. R2R production is a continuous, high throughput, fast and low-cost manufacturing method which is also widely used in the printing of newspapers and magazines. Therefore, it is a mature technology that has been used extensively for a long time. In R2R processing, a flexible substrate is transferred between two rotating rolls, during which various processes are applied to the substrate (Özbilgin, 2016).

An encapsulation is the last process in OPV manufacturing. The stack must be mechanically protected, and water and ambient air penetration should also be kept to a minimum for increased operational stability and longer lifetimes. R2R lamination is a simple and reliable process in which two webs are fed together and joined by an adhesive substance (Özbilgin, 2016).

3.6.3 State of the art – Organic photovoltaic (OPV) cell

Two important aspects (efficiency and life) are responsible for big business potential of OPV. OPV has seen increase in the efficiency year by year due to huge research and development in the field. Figure 15 shows the development of the efficiency in last 10 years (green line) compared to other technologies (Leo, 2013).

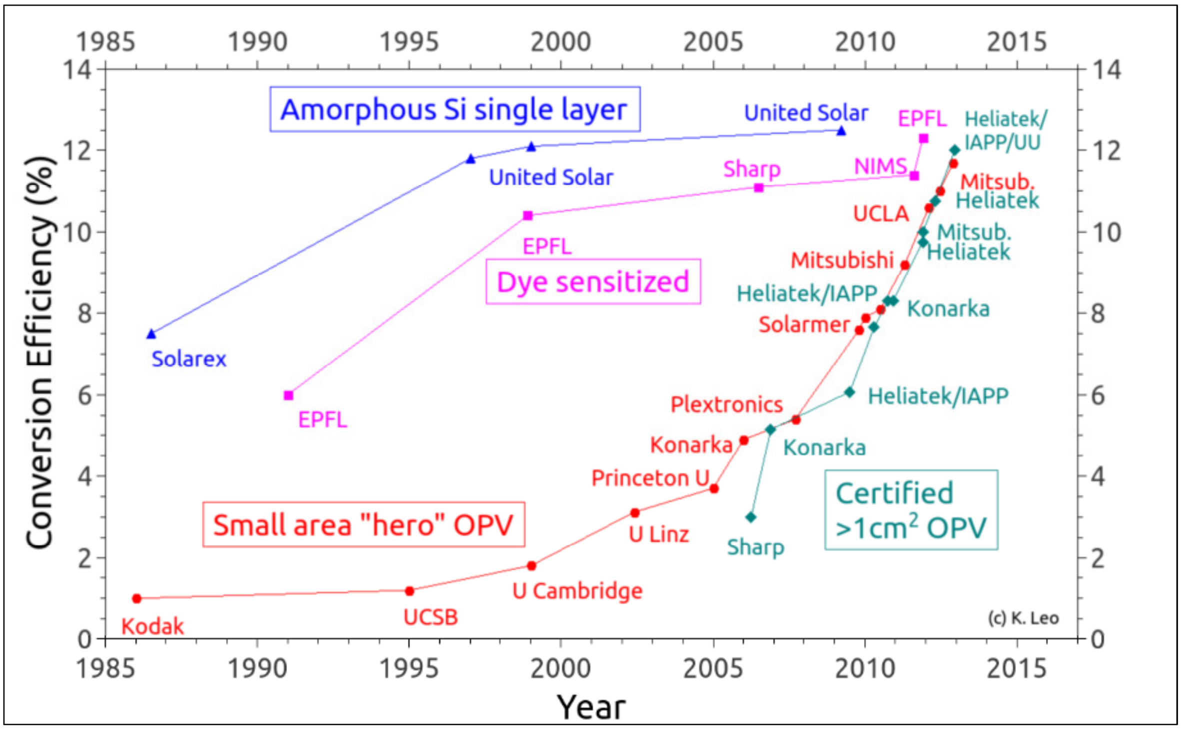


Figure 15 Development in efficiency of OPV from 2005 to 2013 (green line) (Leo, 2013)

Development in the life of OPV is evaluated at the laboratory scale and expects that long life is possible (>20 years) is possible for OPV. Figure 16 shows the result of reliability test on OPV cell manufactured by *Heliatek GmbH*. Result shows that the foil-encapsulated solar film withstands lifetime test well above industrial standard PV limits. However, OPV industries believe that life is not dominant factor when OPV cell has high efficiency and low production cost. At end of the life of OPV, pre-replacement can be done (Leo, 2013). Some researchers believe that to achieve competitive cost of electricity, increase in efficiency to 15% and lifetime to between 15-20 years would be needed (Kalowekamo, 2009).

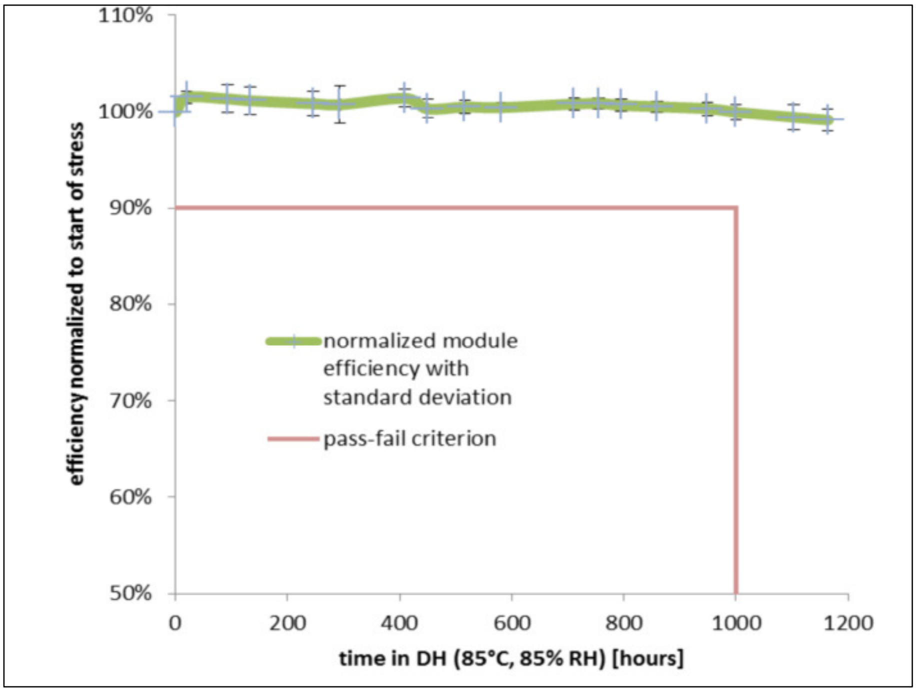


Figure 16 Reliability test result of OPV from Heliatek (Leo, 2013)

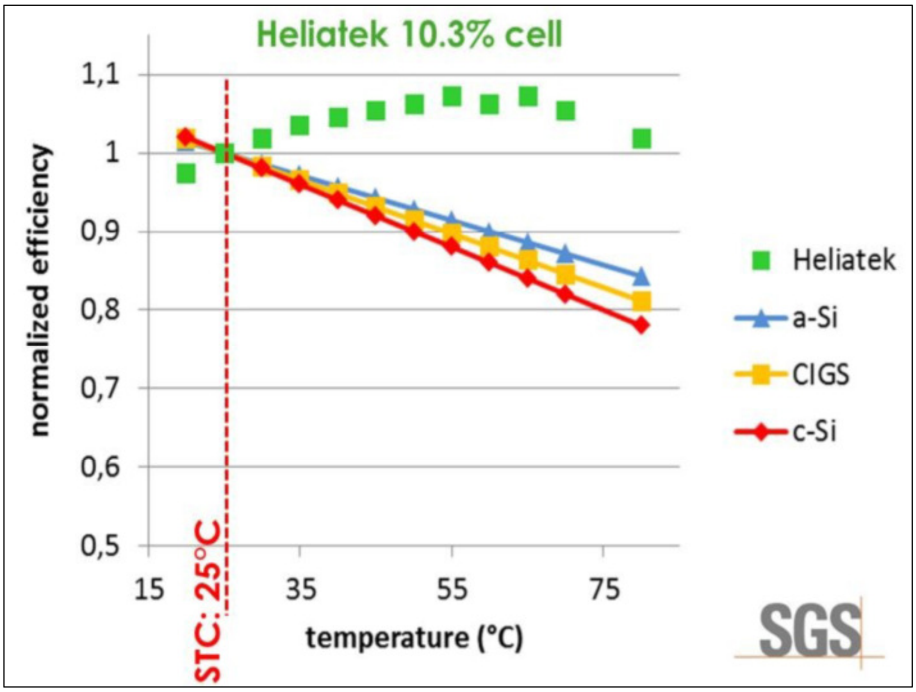


Figure 17 Positive temperature coefficient of OPV cell from Heliatek (green squares) (Leo, 2013)

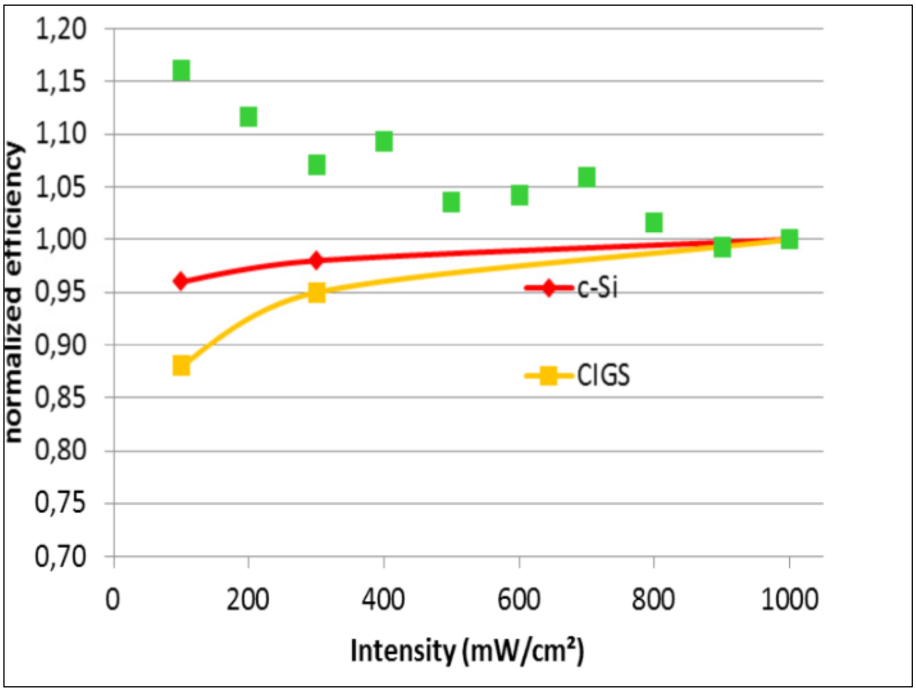


Figure 18 Low light performance of OPV from Heliatek (green squares) (Leo, 2013)

Heliatek is into the manufacturing business of OPV. Key highlights of the product from *Heliatek* are positive temperature coefficients and superior low light performance. A conventional solar cell has reduction in efficiency with the increase in temperature. However, the efficiency of OPV from Heliatek is increase from the temperature increase from 30˚C to 60˚C (Leo, 2013). This is the unique positive point when integration with the solar thermal collector is evaluated. Figure 17 shows the change in efficiency with increase in temperature for OPV from *Heliatek* and other conventional solar cells and Figure 18 shows the measurement result of OPV and other conventional solar cells at different solar irradiation level. *Heliatek* is capable to produce OPV 0.3 m in width and 500 m in roll form with the present state of manufacturing set-up of roll-to roll vacuum vapor process. *Heliatek* can produce OPV in opaque and transparent construction. However, transparent OPV has lower efficiency compared with opaque one. *Heliatek's* pilot installation of OPV proves that it is possible to fix OPV on surfaces like concrete, steel, polymer, glass, foils, aluminum and PVC membrane.

3.7 Production cost estimation

Estimating production cost soon after research and development of product can provide a good indication on project viability. Even-if some information is missing; early estimation of production cost is sufficiently accurate to shade light on product's long-term viability (Anderson, 2009). Production cost is the cost incurred by a business in manufacturing a good and providing a service. Production costs include variety of expenses like labors, raw materials, consumable supplies, general overhead and taxes levied by the government.

In production, there are two types of costs – direct and indirect costs. Direct costs for manufacturing are material used and labors required to produce the finished product. Indirect costs include rent, utility and maintenance expenses (Investopedia, 2017).

Production costs are estimated to decide on the sales price of the product. When sales price is higher than production cost then difference is considered as profit and reverse as loss (Investopedia, 2017).

Further distinction of the production cost is between fixed costs and variable costs. No cost is completely fixed or completely variable. Fixed costs are the costs which are going into producing the product and not going related to the volume of production such as rent, insurance and salaries. Fixed cost such as rent and equipment can be managed through long term agreements. Variable costs are the costs which are related to the output of the production. These costs are direct material cost and direct labor cost. The phenomenon of fixed and variable costs is important when the production cost per unit is the aim of calculation. Variable costs per unit stay relatively stable whereas total variable costs change proportionally with number of units produced. Fixed cost per unit decreases with increase in production. Thus, a business can achieve economies of scale when it produces enough units to amortize the same amount of fixed cost over more units produced and sold. A business with large fixed costs and stable variable costs in their manufacturing process tend to have high amount of the operating leverage. This means that after a company achieves the breakeven point, any further increases in sale will produce higher profits in proportion to sales increase for a business up to a point where fixed costs per unit sold become negligible. On the contrary, decrease in sales volume can produce high decline in profits (Investopedia, 2017).

For estimation made in early stage of product development, determining which costs are fixed and which are variable, and then assigning them on complete dependence or independence from production volume, will facilitate the development and use of a cost-estimating method (Anderson, 2009).

3.8 Business model

Business model is defined to maximize the efficiency and to create a competitive advantage along the value chain of the product. Efficiency and effectiveness of the business is assessed through gross profit on the product. Gross profit is calculated by subtracting cost of goods sold from revenue (Investopedia, 2017). There are different types of business model in practice based on the nature and expectation of the business. They are basically – business-to-business (B2B), business-to-consumer (B2C), and consumer-to-consumer (C2C) and so on. Business-to-business (B2B) refers to a situation where one business makes a commercial transaction with another. This typically occurs when a business is sourcing materials for their production process, a business needs the services of another for operational reasons, a business re-sells goods and services produced by other (Wikipedia, 2017). B2B business model is for horizontal market place where product or services are used by several businesses (Wiki, 2017). B2B business model represents a company centric model.

In most cases, the overall volume of B2B transactions is much higher than the volume of B2C transactions. The primary reason is that in a typical supply chain there will be many B2B transactions involving subcomponents or raw materials whereas only one B2C transaction, specifically sale of the finished product to the end customer (Wikipedia, 2017).

In B2B business model, sourcing of the commodity products like raw materials are in large volume in the competitive market which results in low trade margin benefit for the seller of the products. On the other side, higher trade margin is possible to achieve when the product does not have direct competition in the market.

3.9 Market potential estimation

Market potential estimation represents the demand of any product or services in the market, regional, national, or international. There are five different methods widely used for estimation of market potential (Waheeduzzaman, 2008). The selection of right method depends on the cost and its simplicity in implementation. These methods are –

1. Method of analogy;
2. Proxy indicators;
3. Chain ratio method;
4. Time series analysis;
5. Multiple regression modelling.

Method of analogy is simple logical relationship between two or more variables on a cross sectional or a time-lag basis. It is the ratio of market potential of one product in one place with another product or same product at different place with a certain economic factor. In this thesis, market potential for bus station in Germany is estimated through method of analogy. The result of regional analysis with population density as economic factor is used for calculation of market size for bus station in Germany. This method makes rough estimation but suitable for implementation in very short time (Waheeduzzaman, 2008).

Proxy indicators is very good method when a direct measure is difficult to obtain. Indirect variables help as proxy. This method can provide robust estimation at low cost and ease in implementation. Proxy variables are susceptible to validity problems. The degree of precision depends on measure itself (Waheeduzzaman, 2008). In this thesis, market size for car washing station in Germany is estimated through proxy indicator method. Numbers of gas stations in Germany are used as the proxy with percentage factor to estimate the car washing stations in Germany.

Chain ratio method is a simple arithmetic technique where ratios are used to reduce the base population. The purpose behind this method is to get the realistic demand. It can provide reasonable precise estimates if the ratios are logical and make practical sense (Waheeduzzaman, 2008). Though robust, the method can offer estimates that are close to real information. It is relatively inexpensive and easy to implement.

Time series modeling can be an excellent method for market potential estimation if longitudinal data for the product are available. Simple regressions as well as sophisticated models are used for this purpose. The regressions are easy to estimates if the data available in the right format. Regression result indicates stationary growth trend. The results are very precise if the quality of data is good. It requires specific skills to perform such estimation (Waheeduzzaman, 2008).

Out of all, multiple regression method is the most complex in nature. The beta coefficients indicate the influence of the independent variables on demand. Proper knowledge and skill in modeling are critical. It is possible to estimate market potential from a linear addition of the “net” of consumption, production, and trade. Input and output analysis, elasticity approach, or net of aggregate consumption-production is difficult to implement in developing countries because of lack of quality of data (Waheeduzzaman, 2008).

The selection of right method depends on objective of research and relevance of the method. Method of analogy, proxy indicators and chain ratio methods are simple to conduct, less time consuming, and relatively in-expensive. But these methods, lack credibility in terms of precision and prediction (Waheeduzzaman, 2008).

4. Methodology

4.1 General methodology

The linear approach was used to calculate the production costs for different OPVT collector concepts which is illustrated in the Figure 19. There are four stage gates on this linear path. These stage gates are:

1) the application scenario identified
2) the concepts defined
3) the production cost tool developed
4) the input data collected and the market size estimated

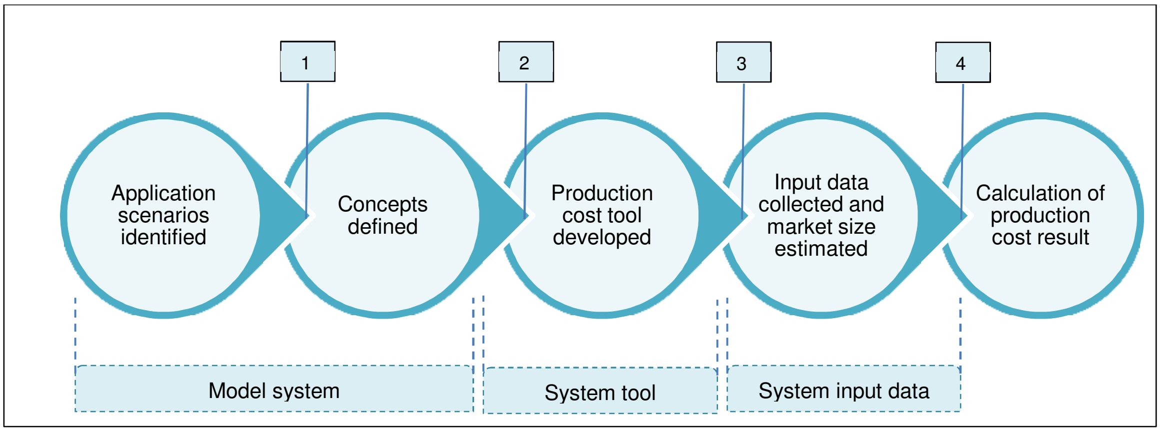


Figure 19 Schematic structure of general methodology

In this chapter, the methodologies for the definition of the application scenario and the concept are elaborated under the model system because it describes the OPVT collector as a system. A methodology for production cost calculation tool development is described under the system tool. The input parameters of the tool and the market size estimation methodologies are explained in the system input data.

4.2 Model system

4.2.1 Application scenarios

Identification of the different applications, selection of most suitable applications and their detailing for concepts were the outcome of the application scenarios.

4.2.1.1 Application identifying

The adaptation of the strategy in choosing either the competitive existing solar thermal market or exploring the new market was the starting point for the selection of application. The present state of technological capabilities and the expectation of higher market volume for the OPVT collector recommended exploring the new application areas. This strategy was also one of the points defined by the German Federal Ministry of Economics and Energy (BMWi) for developing the full potential of solar thermal technologies. Broadly, these strategies advised to discover the new market segments like public and commercial; and explore the new solar thermal application areas. Figure 20 represents the overview on probable market potential in both the market types.

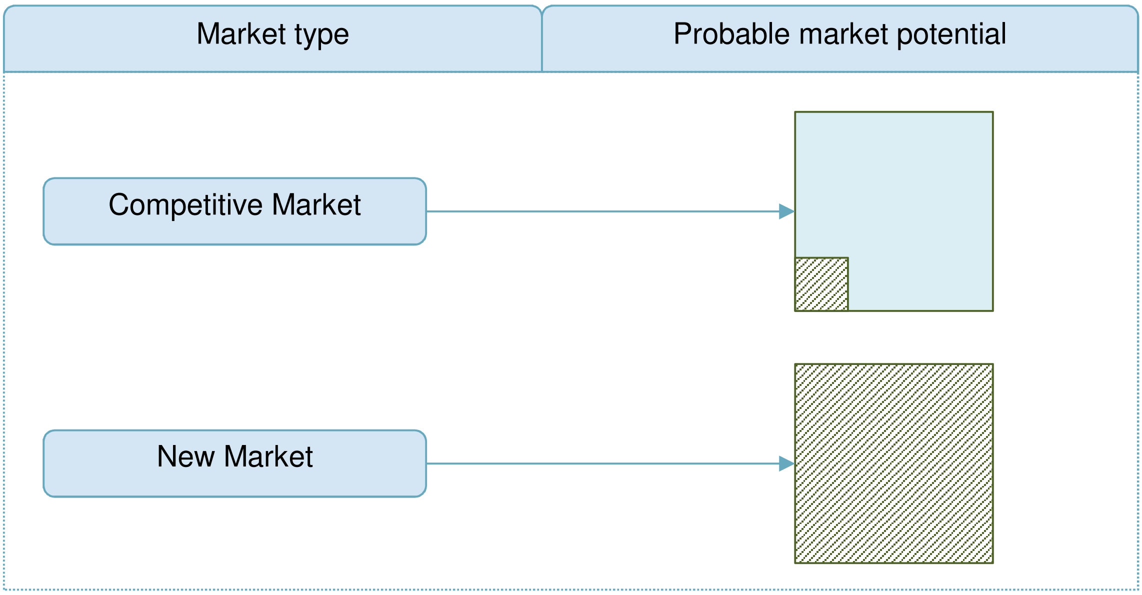


Figure 20 Overview of the probable market potential (hatch area) in both the market types

The selection of applications was started with considering the public and the commercial market segments. The public segment was defined based on the usage of the application by the mass of the people whereas the commercial segment was defined for the usage of application by the specific user. Both the market segments were studied for the different application areas. These application areas were transport management, recreational, hygienic services, event management, waste management, and the agricultural. The transport area was studied for people's management for the public segment whereas for vehicle and traffic management for the commercial segment. The recreational areas were studied for the services related to the leisure and the hygienic services were studied for the cleaning. The event management, the waste management and the agricultural areas were studied for the different applications in the respective areas. The result of the study for each of the application of area is listed in the Table 1. Each of the applications was studied for the output of the OPVT collector and categorized them as mandatory (M), optional (O), and possible to explore (E). For example, the hot water is mandatory for the car washing application; the drying of the sewage sludge by hot water is optional and providing the weather shelter for bus station through hot water or hot air is possible to explore.

Table 1 Analysis of the market segments and the application area for the OPVT collector (Mandatory-M, Optional-O, Possible to explore-E)

Market segment	**Application area**	**Application**	**Output Requirement**		
			Hot Water	**Hot Air**	**Electricity**
Public	Transport	Bus station	E	E	M
Public	Recreational	Zoo	M	O	M
Public	Recreational	Park	O	O	M
Public	Hygienic	Toilet booth	M	O	M
Public	Hygienic	Sanitary container	M	O	M
Public	Recreational	Museum	O	M	M
Public	Event	Air Dome	O	M	M
Commercial	Transport	Camping vehicle	M	M	M
Commercial	Recreational	Weekend home	M	O	M
Commercial	Waste management	Sewage sludge drying	O	M	M
Commercial	Agricultural	Crop Drying	O	M	M
Commercial	Transport	Car washing station	M	M	M
Commercial	Transport	Car parking building	M	E	M

4.2.1.2 Application selected

Each application was analyzed with the unique capability of the OPVT collector. The unique capability of the OPVT collectors were assumed as decentralized, modular, aesthetic and mass production from the features of polymer solar thermal collector and OPV. The ranking for the favorable condition such as (1) for the highest, (0) for the neutral and (-1) for the lowest was given after analyzing each application for each unique capability. Table 2 represents the application ranking for each unique capability of the OPVT collector and results respectively. All the applications except zoo, park and museum are found to be at the remote location. An integration of specific size of the module for the entire application is possible for all the applications except for zoo and park. The aesthetic look of the application is expected for all the applications except for the sewage sludge and the crop drying. The applications, zoo, park and the museum do not favor the mass production possibility.

Table 2 Ranking of applications for the OPVT collector (Highest: 1, Neutral: 0, Lowest: -1)

Application	**Unique capability of the OPVT collector**				**Ranking result**
	Decentralize	**Modular**	**Aesthetic**	**Mass Production**	
Bus station	1	1	1	1	**4**
Zoo	-1	-1	1	-1	**-2**
Park	-1	-1	1	-1	**-2**
Toilet booth	1	1	1	1	**4**
Sanitary container	1	1	1	1	**4**
Museum	-1	1	1	-1	**0**
Air Dome	1	1	1	1	**4**
Camping Vehicle	1	1	1	1	**4**
Weekend home	1	1	1	1	**4**
Sewage sludge drying	1	1	0	1	**3**
Crop Drying	1	1	0	1	**3**
Car washing station	1	1	1	1	**4**
Car parking building	1	1	1	1	**4**

The ranking results and the discussion at the various stages of brainstorming session with the respective experts of the Fraunhofer ISE and the industries were used for the selection of the application. Bus station and toilet booth were chosen because of small applications, ease in integration and promising for demonstration of prototype. Manufacturers and suppliers of car washing station (Janik, 2007), car parking building (Goldbeck, 2017), air dome (Heliatek, 2015) have started showing interest towards usage of renewable energy technologies. And at prima-facie, these applications seem to have big market potential which insisted on choosing them. Sanitary container is quite similar with the car washing application but on the smaller scale. Hence, it is not selected for further detailing. Sewage sludge drying and crop drying have already market for solar technologies but very limited market share has been captured. Crop drying at farm level is still not addressed by the specific solar technology (Ecofys, 2005). Zoo, recreational park and museum are not selected because of two facts. One is no big market and second is requirement of heating as well as cooling load. In this thesis, solar assisted cooling is not studied for the OPVT collector. The weekend home is part of the façade integration for residential building which will be addressed in the project separately. Figure 21 is the pictorial representation of selected applications for further detailing.

Figure 21 Pictorial representation of the selected application

4.2.1.3 Application detailing

Dimensions, area, mounting position, orientation, desired temperature of the fluid and output utilization were studied for each of the chosen applications. Dimension is the overall size of the application. Area is the minimum area available for the installation of OPVT collector/s. Mounting position refers either to the roof mounting or the side face mounting. Orientation defines direction of the collector as vertical, horizontal and/or inclined. Output utilization recommends the possible usage of thermal and electrical output of the collector. Table 3 shows the result of the detailing of each application for above mentioned criteria. These criteria for the application detailing were selected as they were the minimum information to start working on the concept for OPVT collector. The companies into the business of the respective applications were studied for the inputs on each of the criteria. The input finalization was referenced from one company due to the huge variations between the competitors of the same application of the product. All the applications were studied, first, for Germany and second for other European countries because of in-sufficient information from one company. Each application will be referred in abbreviated form wherever necessary from this point onwards. The car washing station as CWS, car parking building as CPB, camping vehicle as CV, bus station as BS, crop drying as CD, and toilet booth as PT. The air dome application was dropped for further consideration in this thesis due to inflatable and material intensive structure.

Table 3 Criteria for application detailing and respective data for the OPVT collector concept

Application criteria				CWS	CPB	CV	BS	CD	PT
Dimension		Length	m	9[1]	50	4.6[3]	3.7[4]	10	1.2[5]
		Width	m	4[1]	16[2]	2.5[3]	1.5[4]	10	1.2[5]
		Height	m	4	2.75[2]	2.6	2.1	10	2.3
Area		Area	m^2	36	44	11.5	5.6	120	1.8
Mounting position		Roof- top	(R)	√		√	√	√	
		Side faces	(S)		√		√	√	√
Orientation		Vertical	(V)		√		√		
		Horizontal	(H)	√		√	√	√	√
		Inclined	(I)	√	√		√	√	
Fluid Output		Temperature	(˚C)	≤ 60	≤ 60	≤ 30	≤ 30	≤ 50[6]	≤ 30
Output utilization	Thermal	Cleaning	kW_{th}	√	√				√
		Drying		√				√	
		Floor heating			√	√		√	√
		Ventilation			√				
		Domestic hot water				√			
		Space heating				√	√		
	Electrical	Lighting	kW_{el}	√	√	√	√	√	√
		Equipment		√	√	√		√	
		Charging			√	√			√
		Advertise panel					√		√

[1] (Washtec, 2017) ; [2] (Goldbeck, 2017); [3] (Hobby, 2017); [4] (Tejbrant, 2017); [5] (Dixi, 2017); [6](Ecofys, 2005)

Car washing stations have different numbers of the bays for washing the car. Each bay is assumed as the uniform in size. Dimension refers to the one bay of the washing station. Orientation of the roof can be either horizontal or inclined. Car parking building structure is varying in length and numbers of floors. Length is dependent on the numbers of cars to be parked on one floor. However, width is possible to defined and referenced from the regulation for minimum length required for the car parking and the minimum clearance required between them (Goldbeck, 2017). Camping vehicle dimensions are referenced from the average dimensions of the camping vehicle offered by the company. Bus station construction is the structure with fixed dimension panels assembled in parallel. Length is calculated by assuming three panels of 1.25 m length kept in parallel. The structure of crop drying facility depends on the volume of the crops to be dried. Dimensions and areas are assumed based on the structure used for sewage sludge drying. Normally, toilet booth has the standard dimensions. Area calculated is for the two side faces of the toilet booth.

4.2.2 Defining the concepts for applications

Task 39 of the solar heating and cooling program (SHC) established by the International Energy Agency (IEA) was the starting point to define the concepts for each application. The polymer based solar thermal collectors and concepts presented in the Task 39 were assessed for the technical parameters such as dimensional and functional for each of the applications. Same technical parameters of the OPV were assessed for integration possibility with the polymer based solar thermal collector. Technical parameters of the OPV were referred from the company *Heliatek GmbH* to limit the variation. The comprehensive assessment was resulted in the illustration of the geometrical classification of the OPVT collector and conceptual sketches of the collector system for each application. At the end, bill of material was derived from the conceptual sketches of the respective applications. Figure 22 is the pictorial representation of the approach chosen for the concept definition.

The dimensional and the functional assessment of polymer collectors defined under the Task 39 and OPV manufactured by *Heliatek GmbH* is described for each applications in the next chapter. Collector classification, conceptual sketches and bill of material are defined for each concepts based on the assessment of the respective applications.

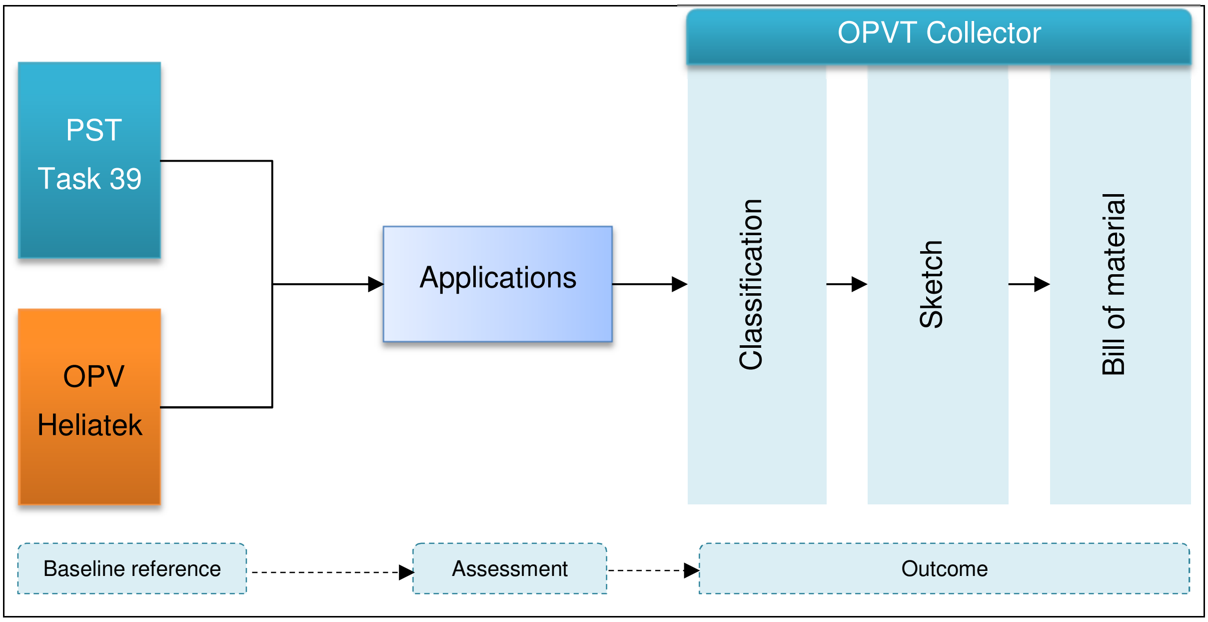


Figure 22 Approach for the concept definition – PST (polymer based solar thermal collector), OPV (organic photovoltaic)

4.2.2.1 Car washing station

A flat plate collector (FPC) was most suitable over thermosiphon system (TSS) and integrated collector storage (ICS) for car washing station. One of the reasons was continuous requirement of the fluid at the specified temperature for cleaning and drying processes. Another reason was length and width of the car washing bay. The flat plate collector from the Norwegian company *Aventa AS* and the pool absorber from the Israeli company *Magen eco-Energy* was selected for dimensional assessment. Both the collectors use water as the heat carrier and dimensionally flexible in length. The constraint in the width for *Aventa* collector was 0.6 m and for *Magen eco-Energy* collector was 1.2 m due to limitations of the injection molding process (Michael Köhl, 2012). However, the modular construction was possible with both the collectors. It means that 15 numbers of the *Aventa* collector and 7 numbers of the *Magen eco-Energy* collector can be coupled for the car washing station. Both the collector types were possible to mount on the tilted roof (Aventa, 2017); (Magen, 2017).

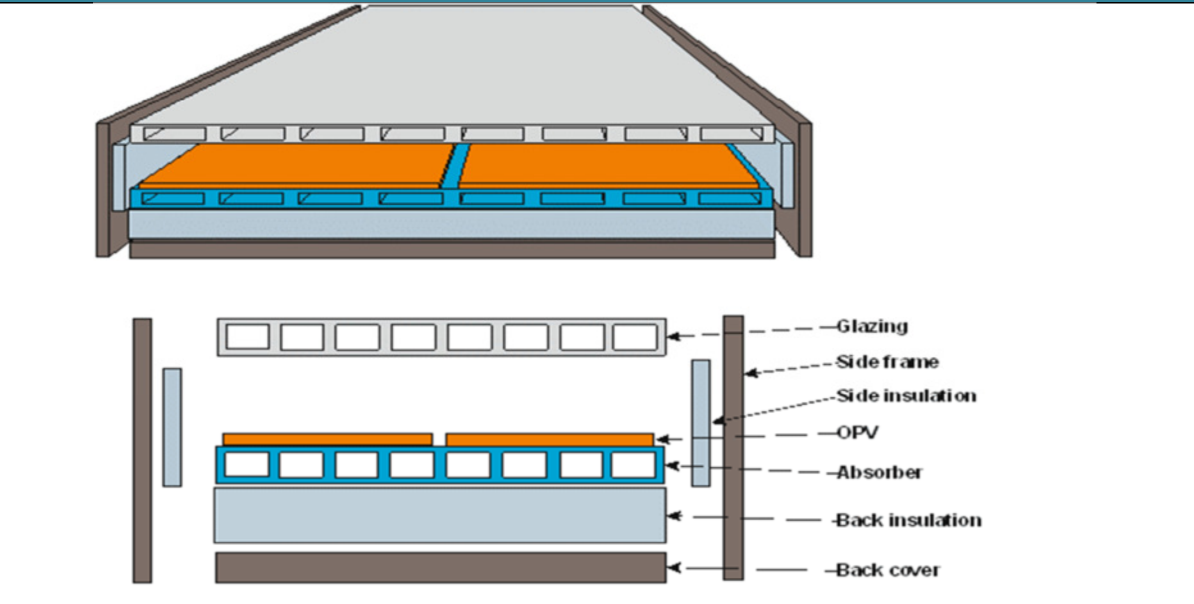
Functionally, higher thermal loss was expected in *Magen eco-Energy* collector as no insulation was used. Hence, the collector from *Aventa* was chosen for the further assessment. The drain-back system was the part of the collector system for the protection of the collector from freezing during cold nights and higher temperature during the peak summer. The stagnation temperature of the collector was the 155 ˚C which was assumed to be suitable for the requirement of the hot water temperature as 60 ˚C for the process (Aventa, 2017). The collector was covered with the polycarbonate twin-wall sheet for increase of its thermal efficiency. The cover was capable of withstanding against weathering effects like UV radiation. The absorber is made up of PPS material and twin-wall construction with 0.5 mm outer wall thickness. This construction of the absorber has higher heat transfer capability despite the fact of lower thermal conductivity of the polymer materials (Aventa, 2017).

The dimensional matching and the fixation of the OPV from *Heliatek* with *Aventa* collector was assessed. The OPV from *Heliatek* is produced in 500 m roll having width of the 0.3 m. The fixing of the OPV with the polymer surfaces is also possible with the appropriate adhesive. Therefore, two numbers of the OPV sheets of 4 m length and 0.3 m width were defined for *Aventa* collector. The opaque OPV was chosen from *Heliatek* because it has higher efficiency compared with transparent OPV and there was no specific requirement for the application which directs for usage of the transparent OPV.

The frames of the collectors from wood polymer composite material were selected because they have lower weight, are environment friendly and possible to manufacture through extrusion process for the desired profile. The sealing is not used for *Aventa* collector. However, sealing was selected to protect the OPV and the absorber surface from the weathering effects and in turn increase of the life and the efficiency.

Table 4 Factsheet for car washing station concept 1 (C1)

Factsheet for Car washing station – Concept 1



Bill of Material (BoM)

Sr. No.	Material item	Quantity (Numbers)	Length (m)	Width (m)
1	Twin-wall absorber	1	4.00	0.60
2	OPV	2	4.00	0.30
3	Glazing	1	4.00	0.60
4	Long frame	2	4.00	-
5	Short frame	2	0.60	-
6	Back cover	1	4.00	0.60
7	Header	2	0.60	-
8	Back insulation	1	4.00	0.60
9	Side insulation	2	4.00	0.05
10	Adhesive	-	4.00	0.60
11	Seal	1	20.00	-

At the system level, storage tank with the auxiliary heating source was found to be appropriate to meet the process demand for the thermal output. Whereas for the electrical output, the consumption of the electricity produced by the OPV was found suitable as electrical appliances are continuously in operation during the process instead of storage. This recommended selecting the inverter in place of the battery. Other standard components like tubes, pump, valves and controller were compulsory for the functioning of the collector. However, size and capacity for each system components could not be decided due to premature level of the technology.

Air collector for the car washing station was not assessed because hot air storage will not be economically feasible.

The outcome of the assessment is defined as the concept 1 in the Table 10 of the OPVT collector classification and as the conceptual sketch in the factsheet Table 4. The numbers of material items per collector, their dimensions, quantities and the unit of measurement were derived based on the assessment described above. This is presented as the bill of material for the car washing station in the factsheet Table 4.

4.2.2.2 Car parking building

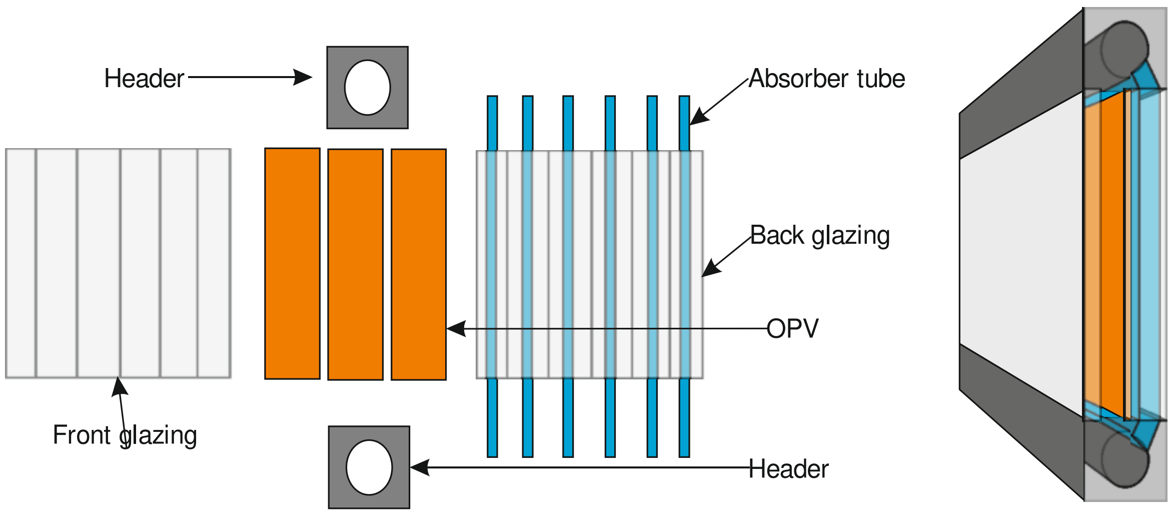
Flat plate collector from *Aventa* and *Magen eco-Energy* were selected for assessment because of the large size of the application. The focus changed to only flat plate collector from *Magen eco-Energy* due to illumination of the car park area through the sunlight during the day (LED, 2010). This is treated as the feature for the companies to save the electricity consumption whereas it is mandatory requirement in some countries. The designed space between two absorber tubes makes it possible with the *Magen eco-Energy* collector.

Dimension of one bay on one side of the car parking is 16 m in length and 2.75 m in height. The collector of 1 m width and 2.7 m length was assessed for the maximum utilization of the space. It means 16 numbers of collectors can be coupled together on the same side. The collector was possible to mount vertically and/or on tilted surface. The absorber tubes of 25 mm diameter with 25 mm gap between two tubes were assumed for allowing the sunlight to pass through the absorber. Two identical headers per collectors, one at the top and another at the bottom, were guiding and supporting the tubes of the collector. The width of the header as 50 mm found to be sufficient for the application.

An encapsulation of the absorber tubes with the multiwall polymer glazing was designed to increase the thermal efficiency of the collector. The stagnation temperature for the *Magen eco-Energy* collector is 150 ˚C (Michael Köhl, 2012) and this was assumed to be suitable for requirement of the hot water temperature with 60 ˚C for the floor heating and the cleaning process. A space available on the face of the headers was directing to use the front cover to minimize the convective losses in the collector. *Magen eco-Energy* insisted on using drain-back system for the protection of the absorber tubes from the reasons explained in the previous chapter.

Table 5 Factsheet for car parking building concept 2 (C2)

Factsheet for Car parking building – Concept 2



Bill of Material (BoM)

Sr. No.	Material item	Quantity	Length	Width
		(Numbers)	(m)	(m)
1	OPV Module	3	2.6	0.3
2	Tube Absorber	20	2.7	0.025
3	Glazing	2	1	2.6
4	Header	2	1	0.05
5	Side Frame	2	2.6	0.05
6	Seal	1	7.2	-
7	Adhesive	-	2.6	1

A face of the encapsulated multi-wall glazing was found to be suitable for fixing of the OPV. 3 numbers of OPV of dimension 2.6 m in length and 0.3 m in width were possible to fix on the face of the encapsulated glazing. The selection of transparent OPV was compulsory for daylight illumination inside the building. 50% of the transparency is possible with the OPV from *Heliatek* but at the reduced efficiency (Heliatek, 2017).

Frames from the wood polymer composites were selected to protect the collector from both the sides and to provide the structural strength to the collector. A use of the sealing was necessary in the modified *Magen eco-Energy* collector for weather protection.

At the system level, components like storage tank, pump, valves and controller were compulsory for the function of the collector but could not be assessed for the size due to the reason described in previous chapter. The use of auxiliary heat source can be eliminated in case the hot water is only used for the floor heating. The electrical storage can be an option if the electrical vehicle charging station is available in the car parking building. Otherwise, the electricity produced by the OPV was decided to be utilized by the electrical appliances used in the building.

An air collector for the OPVT was not assessed due to existence of commercial market of solar air collector for such application.

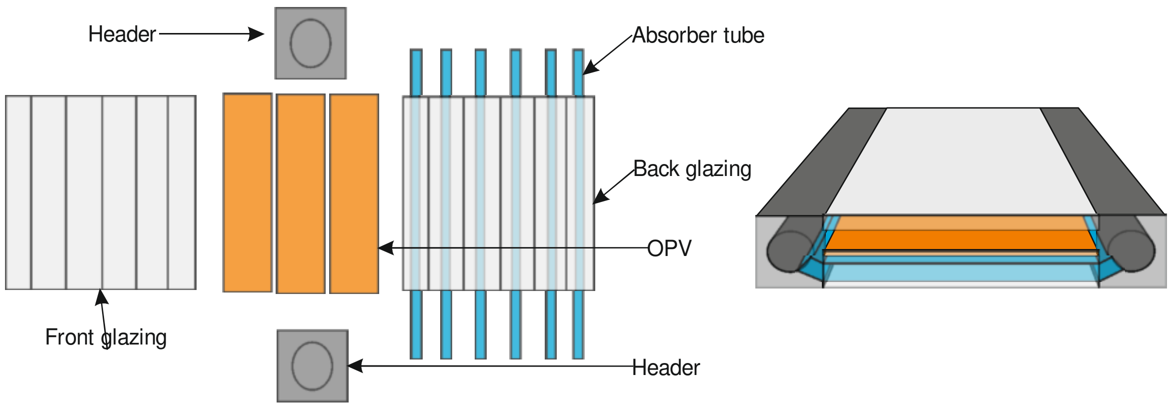
The outcome of the assessment is defined as the concept 2 in the Table 10 of the OPVT collector classification and as the conceptual sketch in the factsheet Table 5. A numbers of material items per collector, their dimensions, quantities and the unit of measurement were derived based on the assessment described above. This is presented as the bill of material for the car parking building in the factsheet Table 5.

4.2.2.3 Camping vehicle

Flat plat collectors from Aventa and Magen eco-Energy, both, were possible to integrate on the roof of the camping vehicle. The integrated collector storage from the UK based company *IDC* was also possible to integrate on the roof of the camping vehicle (IDC, 2008). However, it was dropped for further assessment due to higher weight on the roof and it may require additional structural components for strengthening of the vehicle walls. The collector from *Magen eco-Energy* with modification described for the car parking building was found most suitable and was selected for the further assessment. Heat generated due to the solar irradiation was carried away by the water and providing the natural cooling inside of the camping vehicle during the daytime. This leads to saving of the energy for cooling and lighting. The dimensional analysis for the collector, which has a width of 1 m and length of 2.6 m was resulting in the coupling of 4 numbers of the collectors per camping vehicle. Rest of the parameters for the collectors found to be in line with the application requirement. However, the length of the OPV, tubes and both the glazing are reduced by 100 mm because of difference in the dimensions of both the application.

Table 6 Factsheet for camping vehicle concept 2 (C2)

Factsheet for Camping vehicle – Concept 2



Bill of Material (BoM)

Sr. No.	Material item	Quantity	Length	Width
		(Numbers)	(m)	(m)
1	OPV Module	3	2.4	0.3
2	Tube Absorber	20	2.5	0.025
3	Glazing	2	1	2.4
4	Header	2	1	0.05
5	Side Frame	2	2.4	0.05
6	Seal	1	6.8	-
7	Adhesive	-	2.4	1

The requirement of system components like tubes, storage tank, pumps, valves, auxiliary heating for thermal output and battery, charge controller and wires for electrical output were expected to be same as defined in the car parking building but the system size will be designed on much smaller scale.

The assessment resulted in the concept 2 but on the smaller scale. Hence, the same concept is followed for the camping vehicle and car parking building applications. Numbers of material items per collector, their dimensions, quantities and the unit of measurement were derived based on the assessment described above. This is presented as the bill of material for the camping vehicle in the factsheet Table 6.

4.2.2.4 Bus station

The collector from the German company *Rothe-Werke GmbH* was assessed for the bus station application. This collector was covered with the thermoformed housing of fixed and compact dimensions which was promising for the bus station roof mounting. The *Magen eco-Energy* collector concept defined for the car parking and camping vehicle applications was applicable to the bus station when it is mounted vertically. However, this option did not worked due to the possibility of tampering of the collector and the decentralized location of the application. The decentralized location was one of the reasons for not analyzing water based collector for the bus station. The size of the housing was 1.8 m in the length and 1.2 m in the width for the collector from *Rothe-Werke GmbH* (Rothe-Werke, 2017). The modification in the dimensions of *Rothe-Werke GmbH* was to be done as length of 1.25 m and width of 1.5 m to match the dimension of the bus station panel. The height of the housing was also possible to reduce as there was no insulation and the collector tubes inside the air collector. The circular cut-out in the center of the housing was required for mounting of the fan. The dimension of the cut-out can be decided during detailed design of the collector. The housing was protected with the glass which was assessed for replacement with the polycarbonate glazing for further reduction in the weight of the collector. The openings on the side faces of the housing were required for the air to come in and go out from the collector.

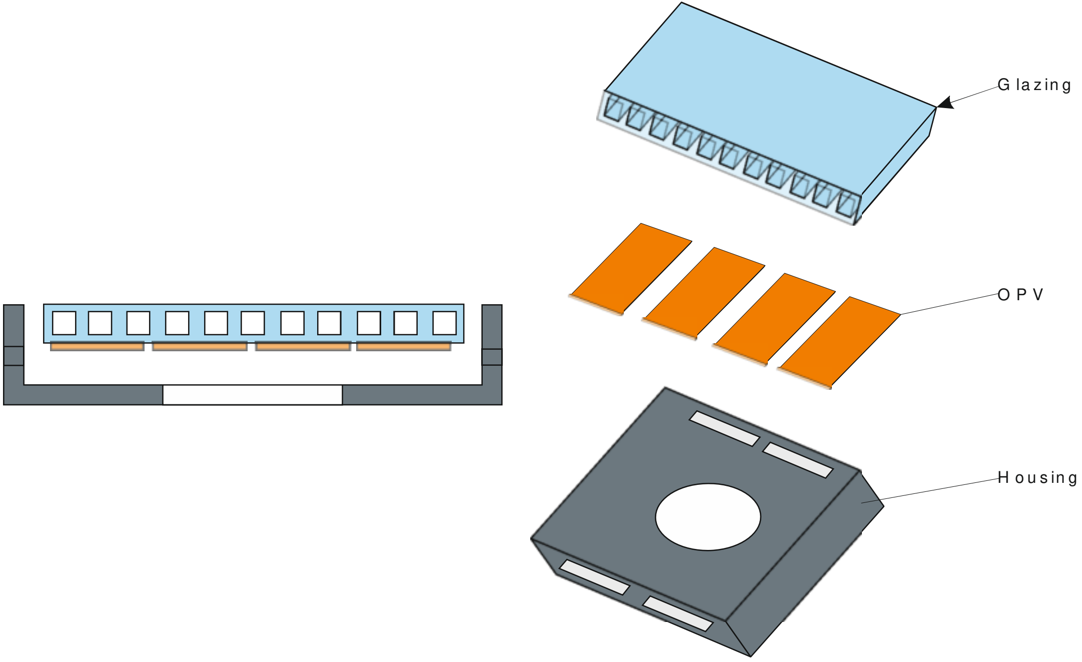
The OPV was decided to fix on the bottom face of the glazing as it acts as the absorber for the collector and the effective heat transfer can happen without considerable pressure loss. The integration of 4 numbers of OPV of 1.5 m in length and 0.3 m in width were possible in the available dimensions of the collector. In case of necessity, the OPV and the housing both were possible to produce as the transparent. However, the opaque OPV and the housing were chosen for the concept.

A use of the louvers was necessary to protect the OPV and inside of the housing from rain, snow, or any foreign particles. Sealing was found to be important between the glazing and the housing for protection of the collector from the weathering effects.

At the system level, two-directional fan was recommended for functioning of the collector during the winter and the summer. A fan with in-built heater was also possible to use for operation of the collector during the night time. For the electrical output, battery storage found to be more plausible for such a small size application.

Table 7 Factsheet for bus station concept 3 (C3)

Factsheet for Bus station – Concept 2



Bill of Material (BoM)

Sr. No.	Material item	Quantity	Length	Width
		(Numbers)	(m)	(m)
1	OPV Module	4	1.5	0.3
2	Housing	1	1.5	1.25
3	Glazing	1	1.5	1.25
4	Adhesive	-	1.5	1.25
5	Seal	1	6	0

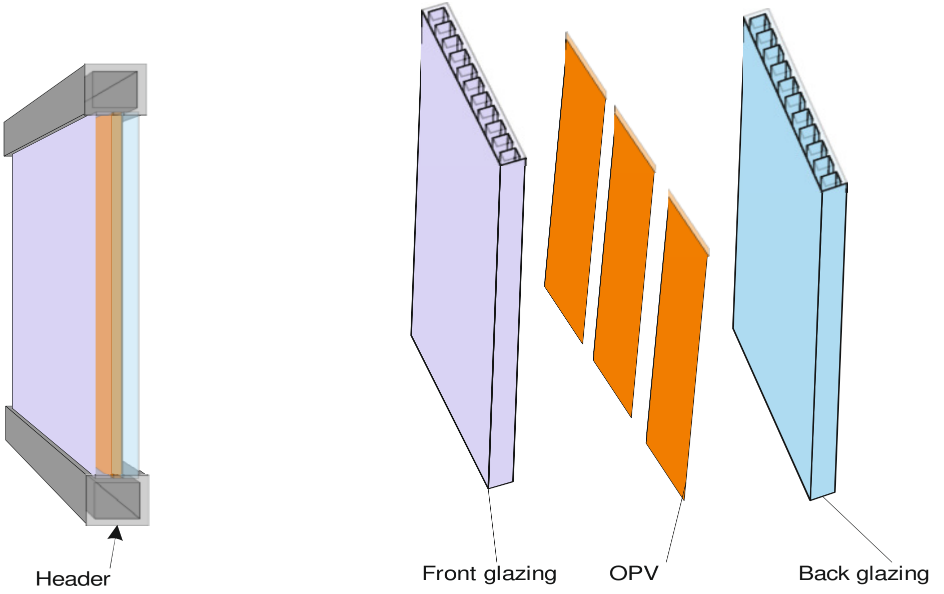
An outcome of the assessment is defined as the concept 3 in the Table 10 of the OPVT collector classification and as the conceptual sketch in the factsheet Table 7. A numbers of material items per collector, their dimensions, quantities and the unit of measurement were derived based on the assessment described above. This is presented as the bill of material for the bus station in the factsheet Table 7.

4.2.2.5 Crop drying

The concept 2 defined for the car parking building was selected for assessment of the crop drying application because both the applications are large and can handle higher volume of the heat carrier. Tubes were not necessary for crop drying because the heat carrier is air. A simple, low in weight, and easy coupling of the collectors was the need for the crop drying because the location of the application in remote area and the seasonal usage of the collector. A multi-wall polycarbonate glazing of 6 m in length and 1 m in width were defined for this application as this glazing provide structural support in addition of handling of large volume of air. 3 numbers of the OPV of 6 m in length and 0.3 m in width were possible to fix on the face of the glazing. A sandwich structure, the OPV between two glazings, was found to be appropriate for protection of the OPV. A bottom and a top end of the glazing are joined with the header brackets for strength. A necessity of opening throughout the width of the header bracket was assessed for the air inlet and outlet. The outcome was 10 numbers of the collector coupled in parallel along the one side of wall and another 10 numbers of the collectors coupled in parallel on the roof of the building structure. The independent structure with collector was also found to be possible due to ease in integration at the remote place like agricultural area.

Table 8 Factsheet for crop drying concept 4 (C4)

Factsheet for Crop drying – Concept 4



Bill of Material (BoM)

Sr. No.	Material item	Quantity	Length	Width
		(Numbers)	(m)	(m)
1	OPV Module	3	6	0.3
2	Glazing	2	6	1
3	Header	2	1	0.05
4	Side Frame	2	6	-
5	Adhesive	-	6	1

An opaque OPV was found suitable when the collector is integrated on the existing construction of the crop drying whereas the transparent OPV was found suitable when going for the independent structure. An OPV as the absorber found to be suitable because the temperature range for stable operation is 45 - 75˚C and temperature of the drying air is less than or equal to 50˚C.

A side faces of the collector were required for the protection of the OPV as well as for the structural strength to the collector. A frame from wood polymer composite was identified for usage in this collector.

At the system level, insulated tubes and blower for the crop drying facility were found to be minimum essential components for the function of the air based OPVT collector. The battery storage for electricity and provision of auxiliary heater were the suitable options as the crop drying at the farm level takes place only in the specific season and even during the night.

The outcome of the assessment is defined as the concept 4 in the Table 10 of the OPVT collector classification and as the conceptual sketch in the factsheet Table 8. A numbers of material items per collector, their dimensions, quantities and the unit of measurement were derived based on the assessment described above. This is presented as the bill of material for the crop drying in the factsheet Table 8.

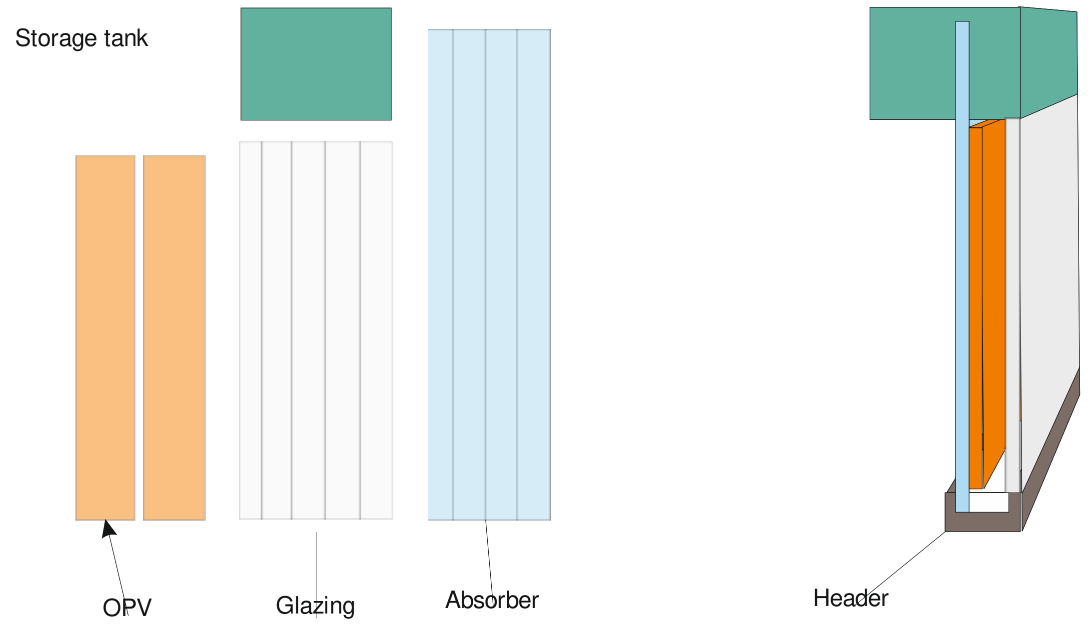
4.2.2.6 Toilet booth

A thermosiphon system from *Aventa* was assessed for the toilet booth because the application is stand alone, small and recommends for less numbers of system level components to limit the cost. The integration of the thermosiphon collector from *Aventa* was found to be easy and plausible due to modular construction of the toilet booth. Each side panel was assumed to be minimum 0.6 m in width and 1.5 m in length. These mounting dimensions were confirming with the thermosiphon system from *Aventa*. For the structural balance and enable availability of the sufficient water for usage, it was necessary to go for two thermosiphon systems in one toilet booth. A size of the storage tank was to be modified for the total capacity of the water as 60 liters and for the dimensions of the toilet booth. The vertical installation of thermosiphon system with storage tank at the backside was already evaluated by *Aventa*.

An absorber used by *Aventa* is manufactured from PP material and in twin-wall construction. The stagnation temperature of the PP absorber is lower than the PPS material used for the flat plate collector. However, the choice of selection of the absorber material is to be made based on the required temperature of the hot water. The use of polymer glazing found to be mandatory for increase of thermal efficiency and reducing the heat loss. Two numbers of OPV of 1.5 m in length and 0.3 m in width were possible to fix on the face of the absorber. The opaque OPV was found suitable for this application.

Table 9 Factsheet for toilet booth concept 5 (C5)

Factsheet for Toilet booth – Concept 5



Bill of Material (BoM)

Sr. No.	Material item	Quantity	Length	Width
		(Numbers)	(m)	(m)
1	OPV Module	2	1.5	0.3
2	Twin-wall absorber	1	1.5	0.6
3	Storage Tank	1	0.6	0.3
4	Glazing	1	1.5	0.6
5	Header	1	0.6	0.05
6	Side Frame	2	1.2	0.05
7	Adhesive	-	1.5	0.6
8	Seal	1	4.2	0

A frame from the wood polymer composite for structural support and easy integration were found appropriate because profile for integration with the toilet booth parts is possible to manufacture through the extrusion process. A use of the seal at the front cover was found to be necessary for the protection of the OPV and the absorber surface.

Battery storage was found to be suitable for the usage of electricity even during night time. Battery storage also enables the provision of electrical socket for charging of the mobile phone.

An outcome of the assessment is defined as the concept 5 in the Table 10 of the OPVT collector classification and as the conceptual sketch in the factsheet Table 9. A numbers of material items per collector, their dimensions, quantities and the unit of measurement were derived based on the assessment described above. This is presented as the bill of material for the crop drying in the factsheet Table 9.

Table 10 OPVT collector classification for all applications

Application	Concept	Type	Fluid	Glazing	OPV	Absorber	Frames
Car washing station	C1	FPC	Water	1 side	Opaque	Twin-wall	WPC
Car parking building	C2	FPC	Water	2 sides	Transparent	Tube	WPC
Camping vehicle	C2	FPC	Water	2 sides	Transparent	Tube	WPC
Bus station	C3	FPC	Air	1 side	Opaque	OPV	WPC
Crop drying	C4	FPC	Air	2 sides	Transparent	OPV	WPC
Toilet booth	C5	TSS	Water	1 side	Opaque	Twin-wall	WPC

FPC - Flat plate collector; TSS - Thermosiphon system; WPC - Wood polymer composite

4.3 System tool

A development of the production cost model started with selection of bottom-up approach for the calculation of the production cost. Identification of the constraints by defining the business model and applying uniformity by defining the manufacturing process plan were the sub-sequent steps after defining the bottom-up approach. A characterization of the output cost was the final step before the production cost model was formulized. The methodology for development of the production cost model is illustrated in the Figure 23.

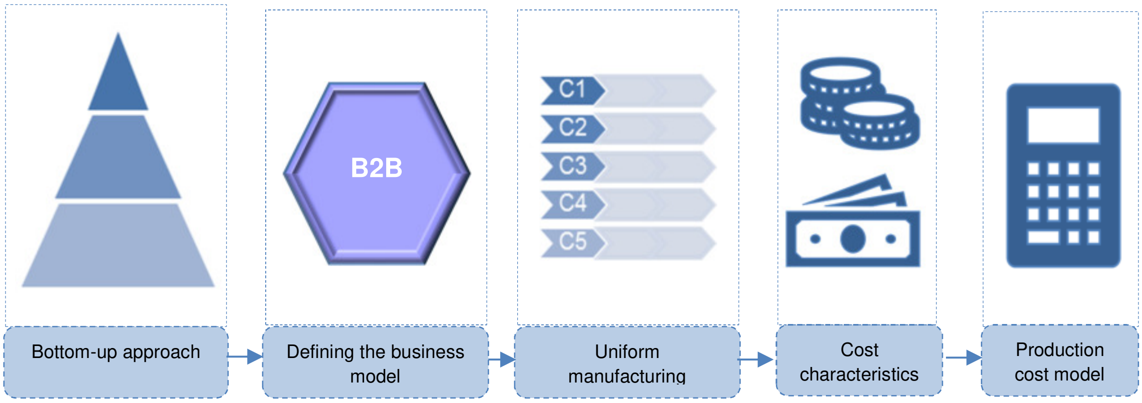


Figure 23 Methodology for developing the production cost model

There are two possible approaches for calculating the production cost. One is the top-down and another is the bottom-up approach (WIKIPEDIA, 2017). In the bottom-up approach, individual elements of the system are defined in detail. These elements are linked together to form the sub-system and sometimes linked to the many levels till the top-level system is shaped. In case of the top-up approach, it is reversed. The bottom-up approach was used for the calculation of the production cost for the OPVT collector concepts because the OPVT collector is at the concept stage and is never been produced before. An estimation of the individual cost element was possible to define and to calculate accurately. Figure 24 represents the bottom-up approach adopted for the production cost calculation.

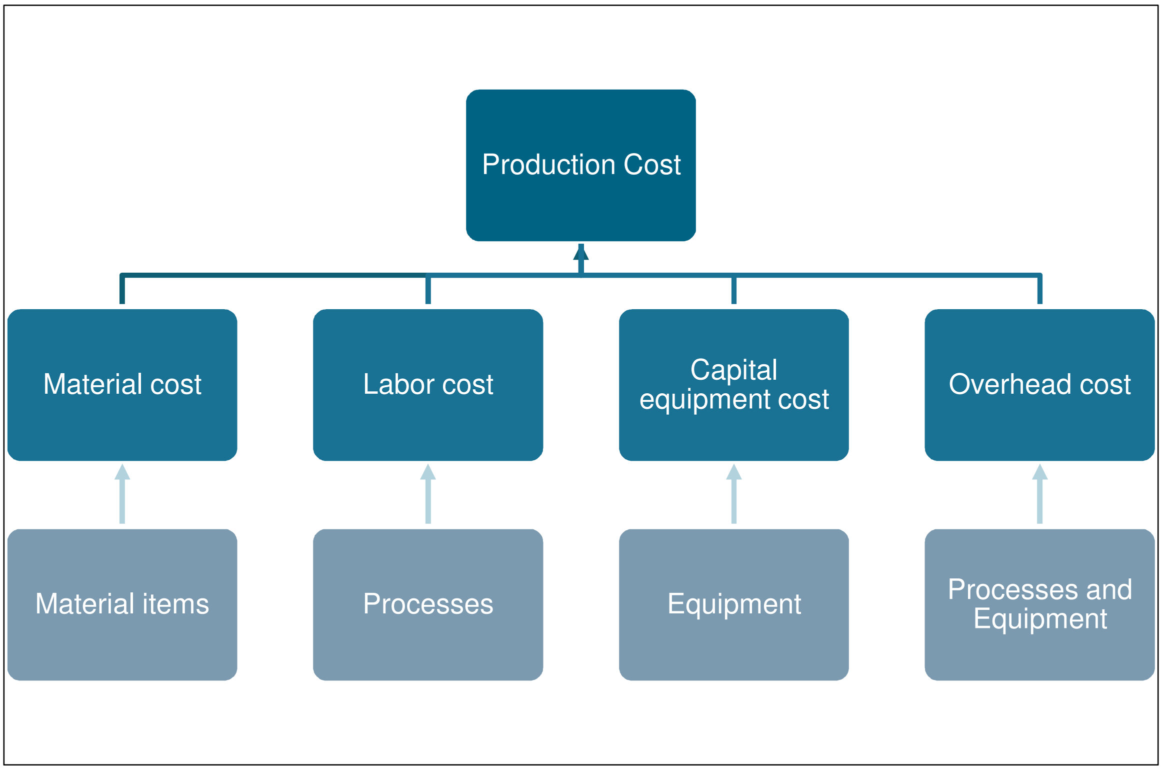


Figure 24 Bottom-up approach for the calculation of the production cost

First, all the five concepts were broken-down into the individual material items, the processes and the machines. All the material items, processes, and machines of the respective concept were linked together to get the material cost, the labor cost and the capital equipment cost respectively. Additionally, all the processes and machines of the respective concept were linked together to get the overhead cost. At the cost component level, all the four cost components were linked together to get the production cost of the respective concepts.

4.3.1 Definition of the business model

A definition of the business model was necessary for the design of the calculation tool because it clarifies the scope of the product business. The Business to Business (B2B) model was found to be appropriate for the calculation tool because the manufacturing level of the material items of the collector and the customer types were illustrating the type of business.

All the items defined under bill of material for each concept are both semi-finished or finished material but not the raw materials. For the manufacturing of the OPVT collector, these items are to be sourced from the respective business area. This defines the boundary at the buying side.

The volume of transaction between the businesses is higher than that with the business to the end customer. It means that the focus should be on more business area on the selling side rather than on the specific segment of end customer. All the applications selected in the chapter application scenario are representing the different business areas. For example, a German based company, *Goldbeck GmbH*, is into the business of construction of multi-storied cart parking buildings. Hence, the car parking building concept for the OPVT collector should be offered to *Goldbeck* and not to the owner or the operator of the car parking building. This defines the boundary at the selling side.

Hence, a scope of the product business is defined as the design, manufacture and supply of the OPVT collector system. A schematic of the B2B model for the OPVT collector is shown in the Figure 25.

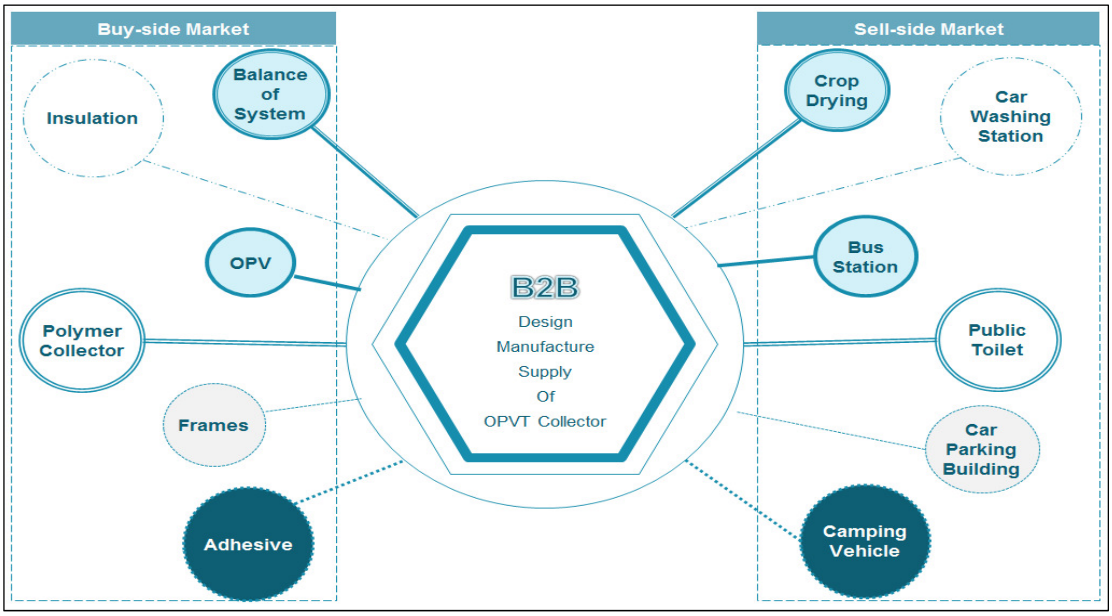


Figure 25 Business model representation for the OPVT collector

4.3.2 Uniform manufacturing process plan

A uniform manufacturing process plan was necessary to define for the user-friendly use of the calculation tool for all the concepts. A manufacturing process plan of any product explains manufacturing processes, machines and labors associated with each process. It also shows the sequential flow path of the product from the raw material to the final product ready for dispatch. In this thesis, there are six applications and five concepts. For the development of the tool, it is easy to use when each concept is manufactured through the same manufacturing process plan. Therefore, common manufacturing steps had to be defined for all the concepts. Five main processes and two sub-processes for each main process were defined which are as follows which are also shown in the Figure 26:

1. Cutting and finishing
    1.1. OPV cutting and finishing
    1.2. Polymer cutting and finishing
2. Mechanical joining
    2.1. OPV and polymer bonding
    2.2. Polymer infrared welding
3. Final assembly
    3.1. Mechanical assembly
    3.2. Electrical assembly
4. Functional testing
    4.1. Pressure testing

    4.2. Electrical performance testing
5. Packing
    5.1. Module packing
    5.2. Balance of system packing

In the next step, types of machines for respective processes were defined through the input from the industrial experts. An automated laser cutting machine was selected for precise cutting of the OPV. A same polymer cutting machine was chosen for cutting and finishing of all the polymer parts due to the properties of polymer parts involved. The bonding process is the most important process for efficient performance of the collector. With the present state of knowledge of expert from *Henkel*, a Germany based adhesive manufacturing company, an automated set-up having the dosing equipment, the robotic dispenser and the handling equipment as a minimum was chosen. Based on the experience from *Aventa*, the infrared welding machine was selected for the welding of polymer parts. Mechanical and electrical assemblies were assumed to be done manually like being followed by different solar thermal collector manufacturing. A machine set-up was assumed for testing of the leakage from the collector and the electrical performance test for OPV part of the collector. For the final process, packing, manual process was assumed for the OPVT collector and the balance of system. Figure 26 shows the schematic arrangement of the uniform manufacturing process plan of the OPVT collector suitable for all the concepts.

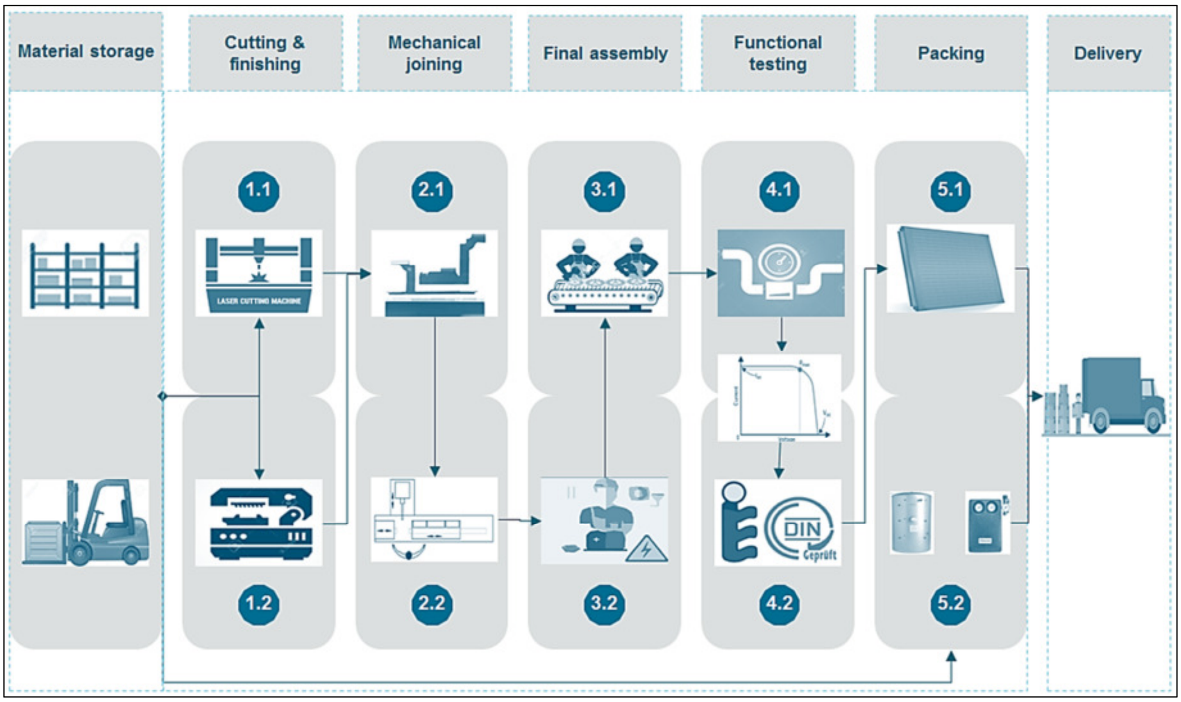


Figure 26 Uniform manufacturing process plan for all the OPVT collector concepts

4.3.3 Characterizing of cost

The approach for characterization of cost as output unit and range is described in the following two chapters.

4.3.3.1 Output unit

There were three output units considered while development of the production cost calculation tool. One is the cost per m^2, second is the cost per module and third is the cost per concept. In this thesis, all the costs and prices are considered as EURO (€) because the location of operational unit is assumed to be in the Germany.

The solar thermal collectors are produced in the different sizes based on the application and optimum cost in the entire value chain of the product. Therefore, it is important to define the common unit which can be used for the various techno-economic analyses and for the comparison between different collectors. In general, cost per m^2 for the production costing and price per m^2 for the product pricing are the units used for the comparison of solar thermal collectors. Hence, one of the output unit was selected as cost per m^2 for the production cost.

The cost per module and the cost per concept are considered as the output unit which will be useful in the interpretation and the selection of the application and/or the concept for prototyping. However, the cost per concept is not calculated in this thesis as the cost of balance of system (BoS) is expressed as the cost per functional output of the collector in terms of cost per kW_{th} and cost per kW_{el}. The cost data on such functional units are possible only with the availability of basic design of the collector and the design of the collector is not possible with the present level of technology.

4.3.3.2 Cost range

A range for the cost was selected in the tool to evaluate the scaling effects of the production on the output cost for each concept. A cost range means the minimum and the maximum value of the cost of the output unit.

Parameters with range were defined based on the level of the technological development, variety in the material types, and in the material manufacturing processes, the production volume, and the geographical locations.

An OPVT collector is the innovative concept and being studied for the feasibility of the business opportunity. Components of the OPVT collectors are representing distinct characteristics. An OPV is still being considered as technological product and not the commercial product like multi-crystalline silicon solar cell. Therefore, range was considered for this gap. The polymer parts have wide variety in the raw material like PP, PPS, PC, PMMA, PE and the manufacturing processes like profile extrusion, tube extrusion, sheet extrusion, blow molding, injection molding, film extrusion, thermoforming. Moreover, bulk purchase of the polymer material reduces the price drastically. These varieties and nature of purchase directed for the range of cost for the polymer items. The manufacturing set-up of the OPVT collector can be automated, manual or combination of both based on the investment capabilities. A manufacturing location has impact either on the land acquisition or the rent of the facility. Hence, the type of manufacturing set-up and the geographical location demanded for consideration of the range. A production volume has the big influence on the cost and the price of the product. The high production volume and the low production cost give the highest revenue to any business. But for the new product, market penetration is the function of many factors other than product features like market type, buyer type, geographical location and market competition. Hence, a range was chosen for the production volume. All these parameters analyzed were represented as the input range parameters in the calculation tool.

In the calculation tool, the minimum cost output refers to all the minimum price of the input range parameters discussed above. While the maximum cost output refers to all the maximum price of the input range parameters. The impact of the production volume is vice versa. The small production volume leads to the maximum cost and the big production volume leads to the minimum cost.

4.3.4 Production cost model

Production cost model is the schematic representation of the production cost calculation tool. The software, Microsoft Excel has been used for development of the tool because it is user-friendly and programmable. It also allows transfer of the production cost calculation into other programming languages. Figure 27 represents the schematic of the production cost calculation tool developed for the OPVT collector for all the six applications and the five concepts. An attribution of the input parameters to the four cost components – material cost (MC), labor cost (LC), capital equipment cost (CPC) and overhead cost (OH) is illustrated as the square symbol. The possible cost types within the cost components are differentiated by the diamond symbol. Dependency of the input parameters for the respective cost types are accumulated horizontally. An output of the possible cost types within cost components is depicted as the ellipse symbol. All the cost types of respective cost components are sum-up vertically and give result of the production cost.

Mathematically, an output of the production cost for each application and respective concept in the tool is expressed as equation (I) for the production cost per module obtained by adding the equations (IV, VII, X, XVI) and as equation (II) for the production cost per square meter of collector area obtained by adding the equations (V, VIII, XI, XII). x in a_x represents the application name and y in $\boldsymbol{c_y}$ represents the concept number. This nomenclature for application and concept is applicable for all the cost components and the production cost.

$$\left(\boldsymbol{PC_{a_x c_y}}\right)_{\boldsymbol{module}} = \left[\left(\boldsymbol{MC_{a_x c_y}}\right) + \left(\boldsymbol{LC_{a_x c_y}}\right) + \left(\boldsymbol{CP_{a_x c_y}}\right) + \left(\boldsymbol{OH_{a_x c_y}}\right)\right]_{\boldsymbol{module}} \tag{I}$$

$$\left(\boldsymbol{PC_{a_x c_y}}\right)_{\boldsymbol{unit\ area}} = \left[\left(\boldsymbol{MC_{a_x c_y}}\right) + \left(\boldsymbol{LC_{a_x c_y}}\right) + \left(\boldsymbol{CP_{a_x c_y}}\right) + \left(\boldsymbol{OH_{a_x c_y}}\right)\right]_{\boldsymbol{unit\ area}} \tag{II}$$

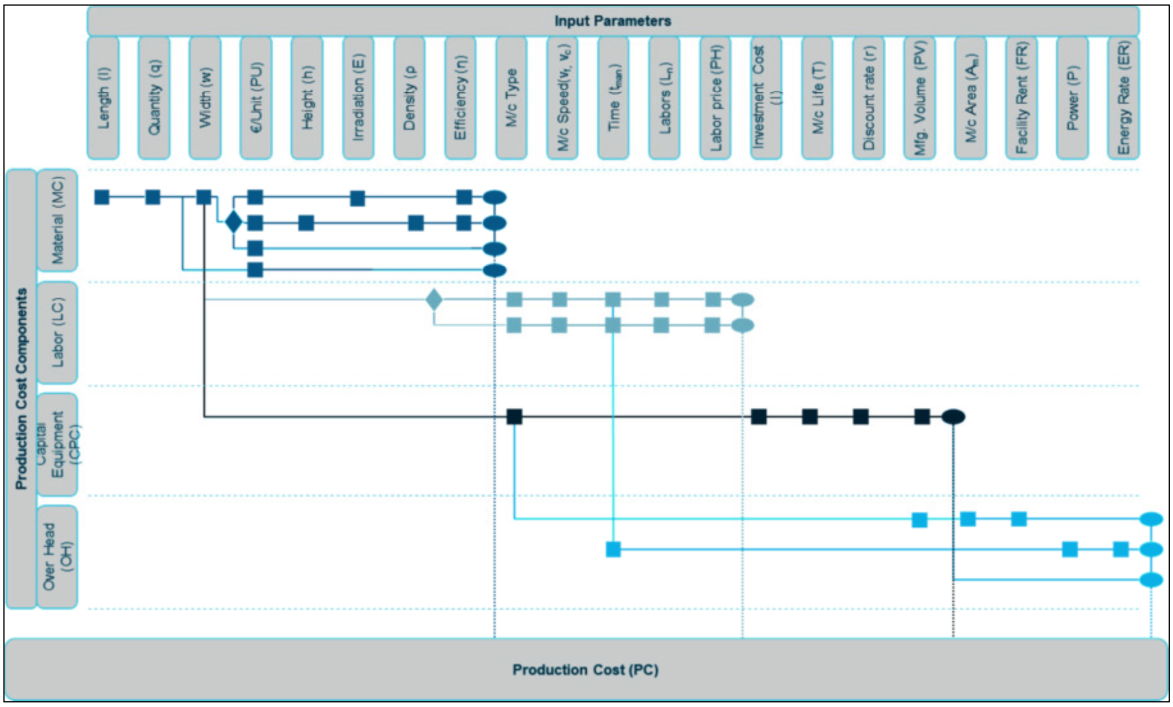


Figure 27 Schematic of production cost model – production cost components (left), input parameters (top), attribution of input with cost component (square symbol), different cost types (diamond symbol), output of cost types (ellipse symbol) and production cost (bottom)

A method for the selection of the input parameters and ab identification of relation between the cost components, input parameter and output is elaborated for respective cost components in the chapter 4.3.4.1, 4.3.4.2, 4.3.4.3, and 4.3.4.4. A definition of each input parameter is documented in the annexure 1.

4.3.4.1 Material cost

Depending on the material item of the concept, four pricing units as €/m^2, €/m, €/W$_p$, and €/kg were identified which were to be represented in the tool. In addition to the pricing units, length (l), width (w), height (h), quantity per module (q), irradiation (E), efficiency (η), and density (ρ) are the input parameters required for the output cost of each of the item. For the uniform approach in the calculation tool, the factors for the respective pricing units were defined. These factors are named as pricing unit factors and they are a_1, a_2, a_3, a_4. The mathematical expression of the material cost of each of the item Mi is defined as the equation (III). i is the index for the material items and n is the numbers of material items per concept.

$$\boldsymbol{M_i} = \begin{bmatrix} (\boldsymbol{a_1} * \boldsymbol{l_i} * \boldsymbol{w_i} * \boldsymbol{q_i}) + (\boldsymbol{a_2} * \boldsymbol{l_i} * \boldsymbol{q_i}) + (\boldsymbol{a_3} * \boldsymbol{l_i} * \boldsymbol{w_i} * \boldsymbol{q_i} * \boldsymbol{\eta_i} * \boldsymbol{E_i}) \\ +(\boldsymbol{a_4} * \boldsymbol{l_i} * \boldsymbol{w_i} * \boldsymbol{h_i} * \boldsymbol{\rho_i}) \end{bmatrix} * \boldsymbol{PU_i} \tag{III}$$

The summation of the output cost of all the items is the amount of material cost per module $\left(MC_{a_x c_y}\right)_{module}$ for the respective concept for the respective application. It is expressed in the equation (IV).

$$\left(\boldsymbol{MC_{a_x c_y}}\right)_{\boldsymbol{module}} = \sum_{i=1}^{n} \boldsymbol{M_i} \tag{IV}$$

The material cost per square meter area $\left(MC_{a_x c_y}\right)_{unit\ area}$ of the collector is obtained by dividing the material cost per module with the area of the collector. Mathematically, it is represented in equation (V).

$$\left(\boldsymbol{MC_{a_x c_y}}\right)_{\boldsymbol{unit\ area}} = \frac{\sum_{i=1}^{n} \boldsymbol{M_i}}{\boldsymbol{A_c}} \tag{V}$$

4.3.4.2 Labor cost

For calculation of the labor cost, the direct labor cost means the cost of labor associated with the process is considered. The labor cost for each process is the function of the process time, numbers of labors required, and price per hour paid to the labors. The process time and the numbers of labors required for each manufacturing process are depend upon the level of automation used. As described in the chapter 4.3.2, the processes were categorized in the automated and the manual. The parameters like length (l), width (w), height (h), quantity per module (q), manual process time $(t_{\boldsymbol{man}})$, numbers of labors $(L_{\boldsymbol{n}})$ and price per hour (PH) were identified as the input parameters for calculation of the labor cost for each process. To enable the function of automated and manual process time in the tool, two additional process factors $(b_1,\ b_2)$ were identified. The mathematical expression of the labor cost of each process (L_j) is defined as equation (VI). j is the index for the sub-processes and n is the numbers of sub-processes per concept.

$$\boldsymbol{L_j} = \left[\frac{\left[\boldsymbol{b_1 * q_j * \left(\frac{l_j}{v_{f_j}} + \frac{w_j}{v_{o_j}}\right) + b_2 * t_{man_j}}\right] \boldsymbol{* L_{n_j} * PH_j}}{\mathbf{60}}\right] \tag{VI}$$

The summation of the labor cost of all the processes is the amount of labor cost per module $\left(LC_{a_x c_y}\right)_{module}$ for the respective concept for the respective application. It is expressed in the equation (VII).

$$\left(\boldsymbol{LC_{a_x c_y}}\right)_{\boldsymbol{module}} = \boldsymbol{\sum_{j=1}^{n} L_j} \tag{VII}$$

The labor cost per square meter area $\left(LC_{a_x c_y}\right)_{unit\ area}$ of the collector is obtained by dividing the labor cost per module with the area of the collector. Mathematically, it is represented in equation (VIII).

$$\left(\boldsymbol{LC_{a_x c_y}}\right)_{\boldsymbol{unit\ area}} = \frac{\boldsymbol{\sum_{j=1}^{n} L_j}}{\boldsymbol{A_c}} \tag{VIII}$$

4.3.4.3 Capital equipment cost

Capital equipment is the machine which requires capital investment at the start-up of the production facility. For the calculation of the production cost, the annual worth is calculated for the capital investment cost of the equipment. The annual worth of each of the equipment depends upon the discount rate (r) and the life of the equipment (T). The capital equipment cost per equipment (I) was obtained by dividing the annual worth of the equipment with the annual production volume (PV_{module}). The estimation of market size for each application is assumed as the production volume capacity of the respective concept. The investment cost of the equipment relies upon the size of the item and the type of operation. Hence, the size (l_1, w_1) and operational factors (m_1, m_2) were added to the function of capital equipment cost for each equipment. And as in some case the equipment is used for more than one operation which guided for the selection of the additional factor as the repetition factor (d_1). The mathematical expression of the capital equipment cost of each of the equipment (CP_j) is defined as equation (IX). j is the index for the sub-processes and n is the numbers of sub-processes per concept.

$$\boldsymbol{CP_j} = \frac{\left[\left[\boldsymbol{l_1 * w_1 * d_1 * I_j *}\left[\boldsymbol{r_j *}\frac{\left(\boldsymbol{1+r_j}\right)^{\boldsymbol{T_j}}}{\left(\left(\boldsymbol{1+r_j}\right)^{\boldsymbol{T_j}}\boldsymbol{-1}\right)}\right]\right] * (\boldsymbol{m_1+m_2})\right]}{(\boldsymbol{PV_{module}})_{\boldsymbol{j}}} \qquad \text{(IX)}$$

The summation of all the capital equipment cost for each concept is the amount of capital equipment cost per module $\left(CP_{a_x c_y}\right)_{module}$ for the respective concept for the respective application. It is expressed in the equation (X).

$$\left(\boldsymbol{CP_{a_x c_y}}\right)_{\boldsymbol{module}} = \sum_{j=1}^{n} \boldsymbol{CP_j} \qquad \text{(X)}$$

The capital equipment cost per square meter area $\left(CP_{a_x c_y}\right)_{unit\ area}$ of the collector is obtained by dividing the capital equipment cost per module with the area of the collector. Mathematically, it is represented in equation (XI).

$$\left(\boldsymbol{CP_{a_x c_y}}\right)_{\boldsymbol{unit\ area}} = \frac{\sum_{j=1}^{n} \boldsymbol{CP_j}}{\boldsymbol{A_c}} \qquad \text{(XI)}$$

4.3.4.4 Overhead cost

The overhead cost has considered the rent, energy and maintenance in the calculation tool. The overhead cost for the rent was defined as the function of the total facility area (A_m), the rent paid (FR) for the facility and the production volume ($PV_{unit\ area}$). The facility area and the rent are directly and the production volume is indirectly proportional with the overhead cost for the rent. The other overhead cost component is the energy. In this thesis, energy refers to the electricity consumed by the equipment during the operation. Hence, the functional relationship between the process time, its electrical power (P) and the energy rate (ER) were established. For the overhead of the maintenance was assumed as the maintenance cost for the capital equipment for respective process. At the root level, facility area is dependent on the size of the module; machine process time is dependent on the machined operation. These relations were introduced in the tool as the size factors (l_1, w_1) and the operational factors (m_1, m_2) respectively. The factor for maintenance cost (e_1) was referred as the industrial standard factor for maintenance. Normally, it is considered as the certain percentage of the respective equipment cost. Mathematically, the overhead cost pertaining to each process and equipment per square meter area of the module $\left(OH_{a_x c_y}\right)_{\boldsymbol{unit\ area}}$ is defined as equation (XII). j is the index for the sub-processes and n is the numbers of sub-processes per concept.

$$\left(\boldsymbol{OH_{a_x c_y}}\right)_{\boldsymbol{unit\ area}} = \boldsymbol{OH_{Rent}} + \boldsymbol{OH_{Energy}} + \boldsymbol{OH_{Maintenance}} \qquad \text{(XII)}$$

Where,

$$\boldsymbol{OH_{Rent}} = \frac{\left[2 * l_1 * w_1 * d_1 * FR * \sum_{j=1}^{n} A_{m_j}\right]}{PV_{unit\ area_j}} \qquad \text{(XIII)}$$

$$\boldsymbol{OH_{Energy}} = \sum_{j=1}^{n}\left[\left[\left(b_1 * \left(\frac{l_j}{v_{f_j}} + \frac{w_j}{v_{o_j}}\right)\right) + (m_1 * t_{man})\right] * q_j * P_j * \frac{ER_j}{(60 * A_{c_j})}\right] \qquad \text{(XIV)}$$

$$\boldsymbol{OH_{Maintenance}} = e_1 * \left[\frac{\sum_{j=1}^{n} CP_j}{A_{cj}}\right] \qquad \text{(XV)}$$

The overhead cost per module of the collector $\left(OH_{a_x c_y}\right)_{module}$ is obtained by multiplying the overhead cost per square meter area with the area of the collector (A_c). Mathematically, it is represented in equation (XVI).

$$\left(\boldsymbol{OH_{a_x c_y}}\right)_{\boldsymbol{module}} = \left(\boldsymbol{OH_{a_x c_y}}\right)_{\boldsymbol{unit\ area}} * \boldsymbol{A_c} \qquad \text{(XVI)}$$

4.4 System input data

The system input data means values of input parameter required for the cost calculation according to the chapter 4.3.4. The collected values are described in the chapter 4.4.1 and the estimated values are described in the chapter 4.4.2.

4.4.1 Data acquisition

There are two categories of the input parameters defined in the chapter 4.3.4. First category is independent parameters and another is range parameters. As described in the chapter 4.3.3.2, the range parameters are sensitive and require accurate input values. On the other side, the independent parameters are the fixed values which are possible to optimize based on the influence on the production cost. The values of input can be considered as accurate when they are received from the industrial experts because industrial experts are into the business of the respective items and can provide the accurate input. Therefore, a questionnaire pertaining to each input parameter was prepared and sent to the respective industrial experts. Feedback from the respective industrial experts was partial because of the company's policy on sharing of the confidential information. Missing values of the input parameters were identified and obtained from the other sources like literatures and web data. Still, there were input parameters whose values were missing. The values of remaining input parameters were assumed. The approach for getting the input data is shown as the schematic in Figure 28. The input data for each application and concept is represented in the annexures 2 to 7.

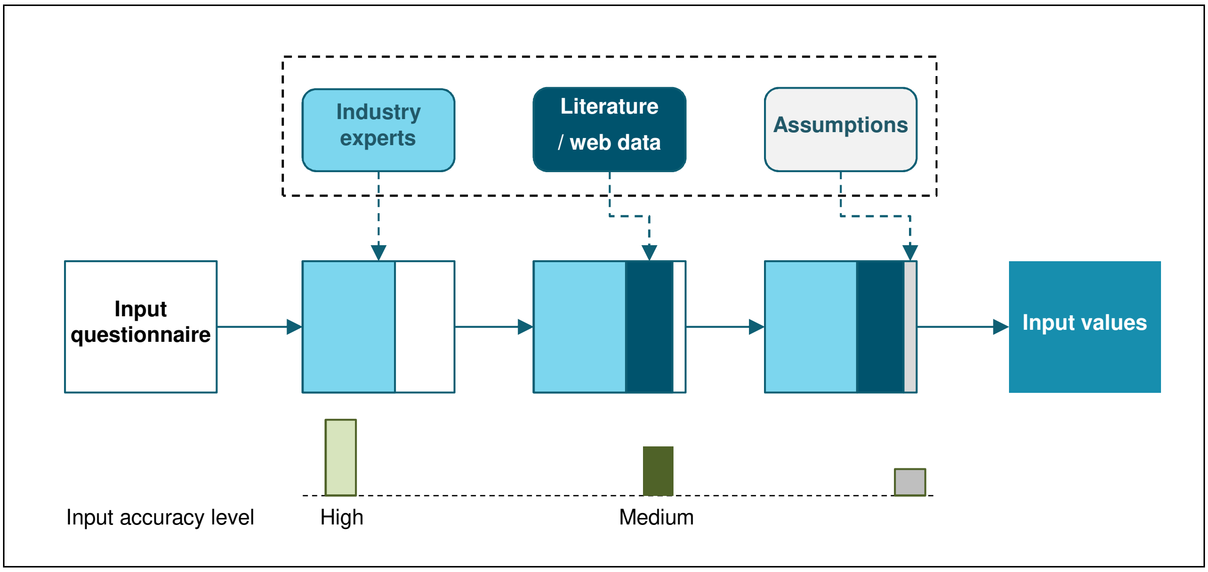


Figure 28 Approach for collecting the values of the input parameters from sources

4.4.2 Market size estimation

Market size is an important factor due to its relationship with the scaling effect of the production as per equation (IX). An estimation of the market size is very difficult for the new market. A market size can be a random number for understanding the behavior of the production cost. However, an application specific market size was decided to estimate because it can be used for making the business decision for promising applications. The numbers for the market size for the respective applications are estimated for Germany.

An estimation of the market size was conducted by categorizing the applications. A direct availability of the information on the market size for the application was considered as the direct category and the numbers for the applications obtained after applying the analytical methods was defined as the indirect category. In the direct category, data for the car parking building (Goldback, 2016) and the toilet booth (Ecotel, 2010) are obtained from the annual report of the market leader of the respective applications. Data for the camping vehicle is obtained from the annual report of the association for the camping vehicle industry (CIVD, 2017). The data for the crop drying is referenced from the Task 29 of the IEA (Ecofys, 2005). In the indirect category, two analytical methods for the market potential are used. The proxy indicator method is used for the estimation of the numbers of car washing station in the Germany. The numbers of gas stations in Germany are used as the proxy for car washing station (Haucap, 2017). Later, the assumption on the proxy numbers was made to include the independent car washing stations in the Germany. The analogy method is used for getting the numbers of bus stations in the Germany. In this method, the result of the regional analysis for the bus station is extrapolated for the whole

Germany. The RVF network in the south Germany was analyzed for getting the numbers of bus stations in the region and density of the population in this area.

An application specific market potential for the OPVT collector was calculated by multiplying numbers of application units with the area available for the installation of the collector. The area available for the installation of the collector for each application is referenced from the chapter 4.2.1.3.

Five scenarios were assumed for the market penetration. These scenarios are – 1%, 5%, 10%, 50% and 100% of the market size estimated for each application. The outcome of each of the market penetration scenarios was applied as the maximum production volume in the tool for the calculation of the minimum production cost for each application Table 11 shows the market size of each of the application and respective numbers for each market penetration scenarios.

Table 11 Market size numbers and market penetration scenarios for all applications

Application		CWS	CPB	CV	BS	CD	PT
Market size of application (units) [A]		12000[1]	408[2]	150000[3]	50000	83040[4]	80000[5]
Application assumption		2 bays/CWS	3 storied, 6 bays/CPB	-	3 panels/BS	-	2 sides
Area per application (m^2) [B]		72	748.8	9.6	5.625	120	1.8
Total Market size (m^2) [A * B]		864000	305510.4	1440000	281250	83040	144000
Market penetration (m^2)	**1%**	8640	3055	14400	2813	830	1440
	5%	43200	15276	72000	14063	4152	7200
	10%	86400	30551	144000	28125	8304	14400
	50%	432000	152755	720000	140625	41520	72000
	100%	864000	305510	1440000	281250	83040	144000

[1] (Haucap, 2017); [2] (Goldback, 2016); [3] (CIVD, 2017); [4] (Ecofys, 2005); [5] (Ecotel, 2010)

5. Results

A calculation tool for the production cost was developed in the “Microsoft Excel” software based on the methods defined under the chapter 4.3. The inputs of all the applications and the respective concepts presented in the annexures 2 to 7 were applied to the calculation tool and the respective results are presented in this chapter.

5.1 Evaluation of the results

The production cost results presented in the Figure 29, Figure 30 and Figure 31 are calculated in €/module and in €/m^2 respectively. For each production cost result, two outputs are calculated, the minimum and the maximum, which represents the range of costs for the respective concept. The share of each cost component on the total production cost is shown in the Figure 31. The contribution of each cost component is shown as the percentage of the total production cost in the Figure 32, Figure 33, Figure 34, Figure 35, and Figure 36 for analyzing the influence of respective range parameters of the cost components. The cost share of material items, processes and equipment are presented as the percentage of respective component cost in the Figure 37, Figure 38, Figure 39, Figure 40, Figure 41, and Figure 42 for the impact analysis. The production cost result against different share of market is analyzed in the Figure 47 for the attractiveness of the market. The market size in the Figure 47 is represented on the X-axis as the logarithmic scale for visualization of pattern of all concepts at one place.

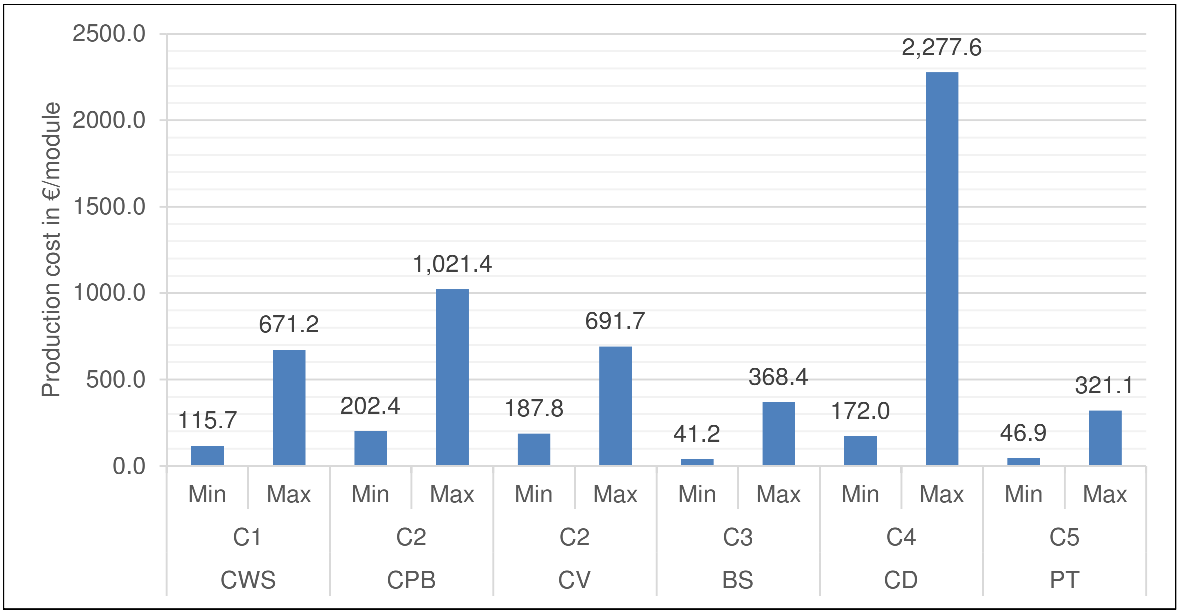


Figure 29 Production cost per module (minimum, maximum) for concepts C1 – C5

The result of the production cost per module for each application and concept is represented in the Figure 29. The concept (C3) for the bus station has the lowest production cost with 41.2 €/module among the minimum costs of all the concepts. The concept (C5) for the toilet booth has the lowest cost with 321.1 €/module among the maximum costs of all the concepts. The concept (C2) for the car parking building has the highest production cost with 202.4 €/module among the minimum costs of all the concepts. The concept (C4) for the crop drying has the highest cost with 2277.6 € among the maximum costs of all the concepts. The concept (C2) for the camping vehicle has the least difference as 72.8% and the concept (C4) for the crop drying has the largest difference as 92.4% between the ranges of the production cost within the concept. The maximum production costs of all the concepts shows the relation with the size of the OPVT module for the respective application, it means, the concept (C5) for the toilet booth has the lowest collector area as 0.9 m^2 as well as the lowest production cost as 321.1 €/module whereas the concept (C4) for the crop drying has the highest collector area as 6 m^2 as well as the highest production cost as 2277.6 €/module.

The production cost in €/module has the correlation with the total area of the collector. All the concepts are having different area of the OPVT collector. The comparison of the production cost at module level is insufficient and is giving the limited information. Hence, a common unit is required for the comparison between the concepts and within the cost components of the concept. The further analysis is done for the cost per square meter of collector area (€/m^2) keeping mind that the collector gains are different.

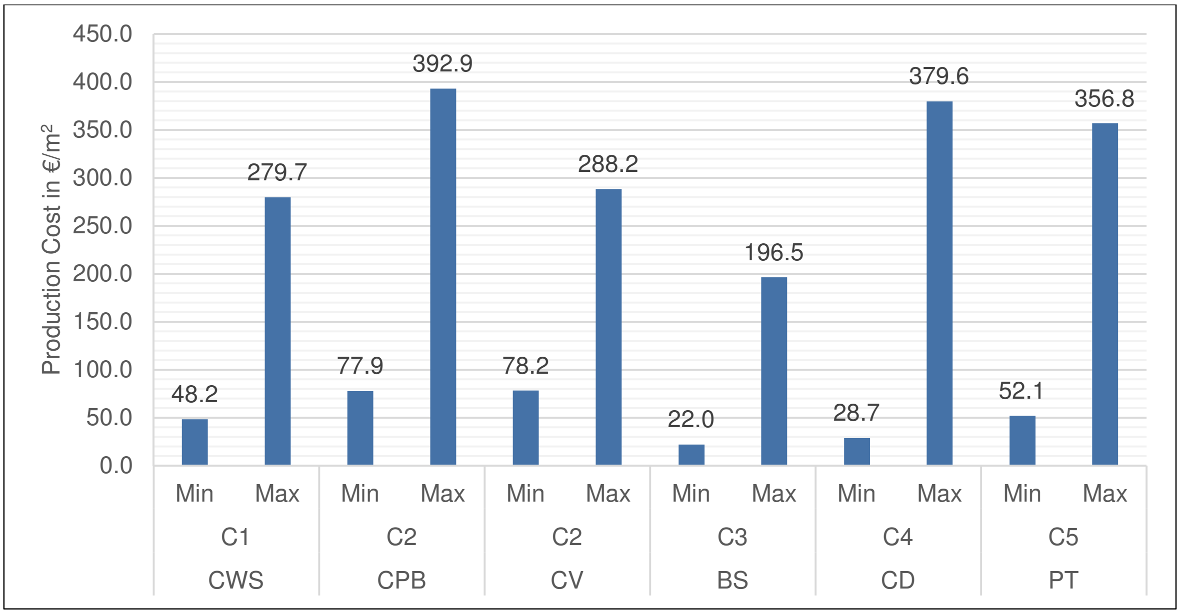
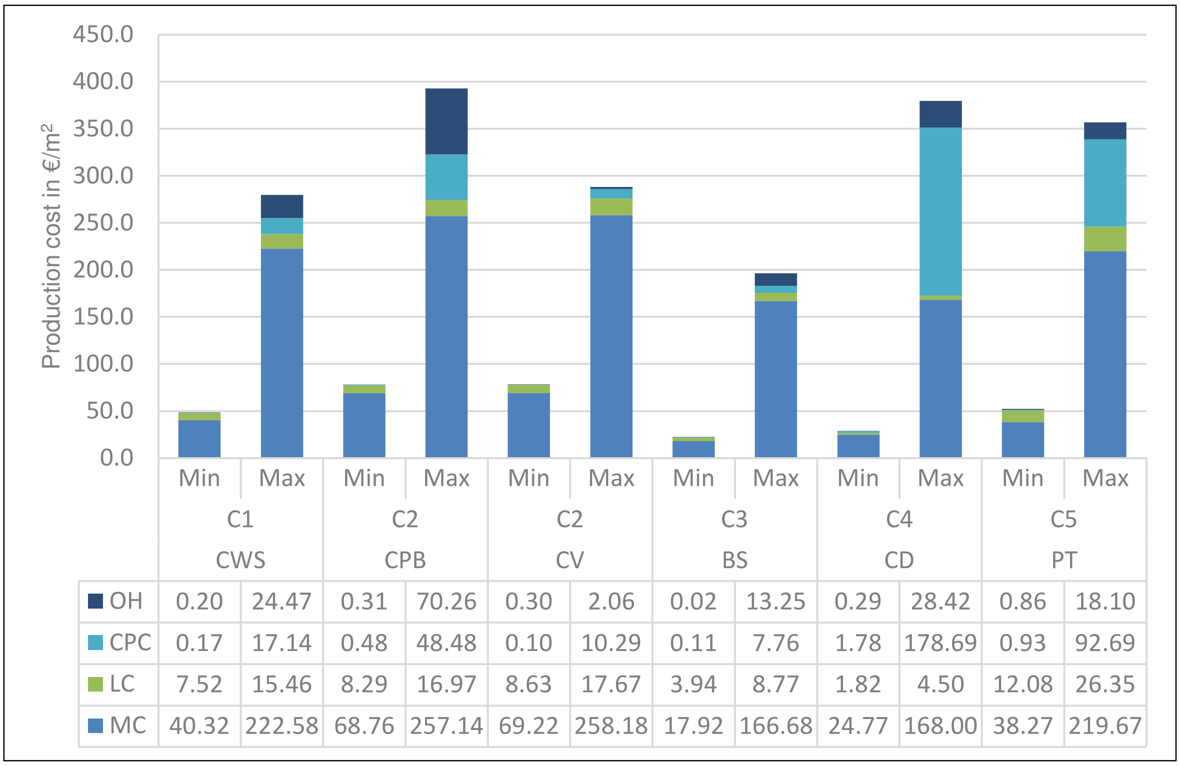


Figure 30 Production cost in €/m^2 (minimum, maximum) for concepts C1 – C5

The result of the production cost per square meter of the collector area for each application and concept is represented in Figure 30. The concept (C3) for the bus station has the lowest production cost with 22.0 €/m^2 among both, the minimum and the maximum, costs of all the concepts. The concept (C2) for the camping vehicle has the highest production cost with 78.2 €/m^2 among the minimum costs of all the concepts. The concept (C2) for the car parking building has the highest cost with 392.9 €/m^2 among the maximum costs of all the concepts. In case of air based OPVT collectors, the concept C3 for the bust station has the lowest cost of production with 22.0 €/m^2 when compared with the concept C4 for the crop drying with 28.7 €/m^2. However, the concept C4 for crop drying has the higher scaling effect than the concept C3 for the bus station when difference between the minimum and the maximum costs of the respective concepts are compared from the Figure 30. In case of water based OPVT collectors, the concept C1 for the car washing station has the lowest cost of production with 48.2 €/m^2 when compared with the concept C5 for the toilet booth with 52.1 €/m^2 and the concept C2 for the car parking building with 77.9 €/m^2 and the camping vehicle with 78.2 €/m^2. However, the concept C5 for the toilet booth has the higher scaling effect than with the other water based OPVT collectors when the difference between minimum and maximum costs of the respective concepts are compared from the Figure 30.



	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max	Min	Max
	C1		C2		C2		C3		C4		C5	
	CWS		CPB		CV		BS		CD		PT	
■ OH	0.20	24.47	0.31	70.26	0.30	2.06	0.02	13.25	0.29	28.42	0.86	18.10
■ CPC	0.17	17.14	0.48	48.48	0.10	10.29	0.11	7.76	1.78	178.69	0.93	92.69
■ LC	7.52	15.46	8.29	16.97	8.63	17.67	3.94	8.77	1.82	4.50	12.08	26.35
■ MC	40.32	222.58	68.76	257.14	69.22	258.18	17.92	166.68	24.77	168.00	38.27	219.67

Figure 31 Production cost break-up in all cost components (MC, LC, CPC, OH) for concepts C1 – C5

The influence of the cost components on the production cost gives the direction for the optimization and which is only possible when each cost component of the respective production cost is analyzed within the concept and compared between the concepts. The contribution of all four cost components in the production cost for each application and concept is shown in Figure 31. The large share of the material costs in both, the minimum and the maximum costs, is found in the entire concept which means the production costs are dominated by the material costs. This high influence of the material cost on the production cost raises the need for a detailed analysis of the material costs for each material item. The labor cost of the concept C5 for the toilet booth is higher than the labor costs for the other concepts which mean the concept C5 for the toilet booth is labor intensive in addition to the dominance of the material cost. The impact of labor cost for the concept C5 is directing for further evaluation of the labor cost for each process. The capital equipment costs for the concept C4 for the crop drying and the concept C5 for the toilet booth are higher than the capital equipment costs for the other concepts. The concept C4 for crop drying and the concept C5 for the toilet booth are guiding for further analysis of the capital equipment cost. The overhead cost for the concept C2 for the car parking building is higher than the overhead costs of other concepts. Despite the same concept for the car parking building and the camping vehicle, the influence of overhead cost is seen only in the car parking building which directs for the comparison of the overhead costs for both the applications.

5.2 Ratio of cost components

The illustration of the contribution of each cost component in percentage of the total production cost for each application concept is shown in Figure 32, Figure 33, Figure 34, Figure 35, and Figure 36 respectively. The material cost is between 68.58% and 88.46% of the minimum production cost whereas it is between 89.58% and 44.26% of the maximum production cost for all the application concepts. The maximum cost of concept (C4) for the crop drying is the exception where it shows the dominance of the capital equipment cost as 47.07% over the production cost. The capital equipment cost as 25.98 % also shows the dominance for the maximum production cost of the concept (C5). The labor cost for the concept (C5) for the toilet booth as 23.17% show the higher contribution on the minimum production cost compare to the other concepts. The overhead cost for the concept (C2) for the car parking building as 17.89 % show the higher contribution on the maximum production cost compare to the other concepts.

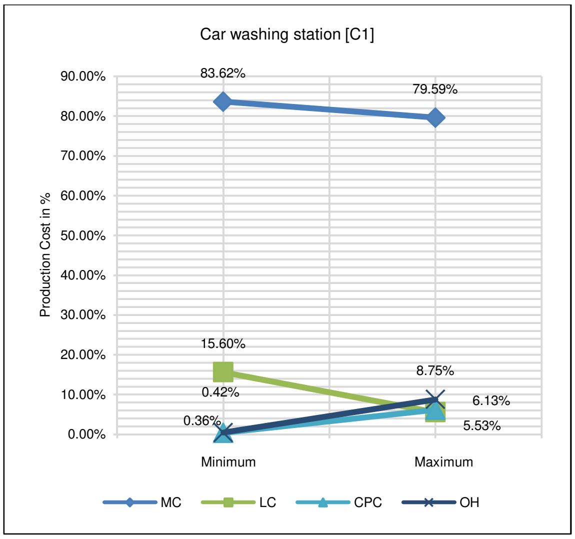


Figure 32 Cost components share on production cost range for concept C1

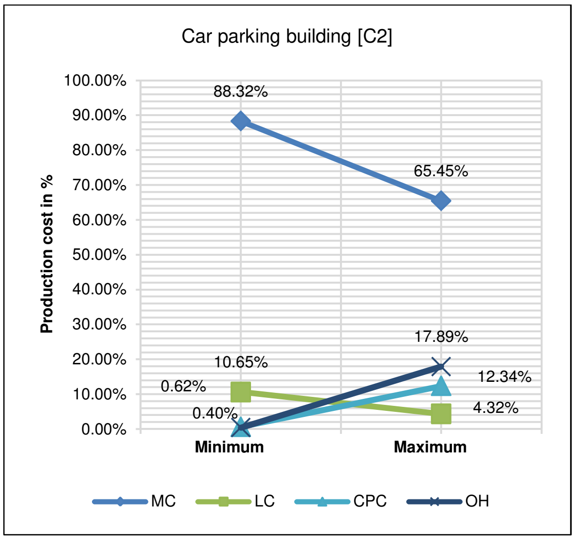


Figure 33 Cost components share on production cost range for concept C2

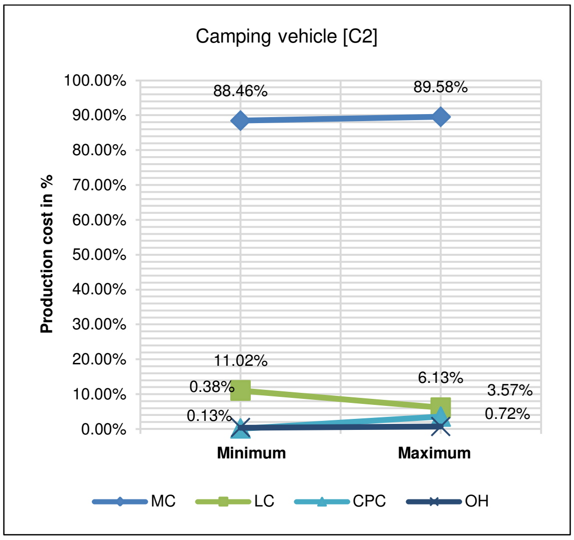
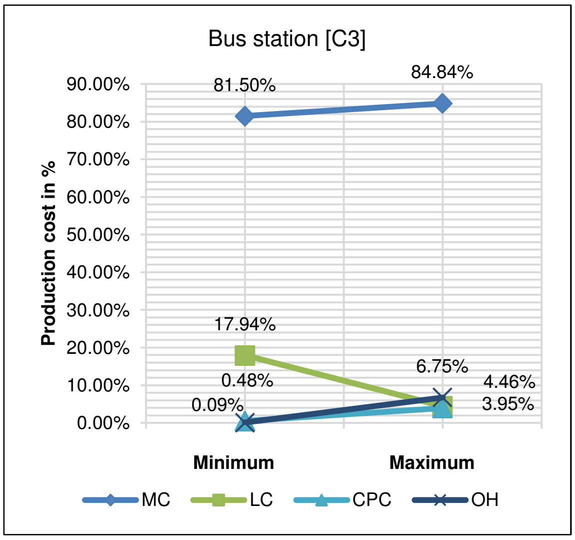


Figure 34 Cost components share on production cost range for concept C2

The concept C2 is same for the car parking building and the camping vehicle applications. However, the capital equipment costs and the overhead costs for the maximum costs are showing the different contributions. The maximum capital equipment cost for the car parking building is 12.34% whereas 3.57% for the camping vehicle and the maximum overhead cost for the car parking building is 17.89% whereas 0.72% for the camping vehicle. Referring to the equation for the capital equipment cost (IX) and (XII) for the overhead cost, the production volume is the influencing parameter for this varying distribution between both the applications that means the car parking building has lower production volume than the camping vehicle. The minimum production volume for the car parking building is 3,055 m^2 and 14,400 m^2 for the camping vehicle as per input data in the annexures 3 and 4 of the respective applications. Therefore, the higher contribution of the capital equipment cost and the overhead cost are present for the same concept.



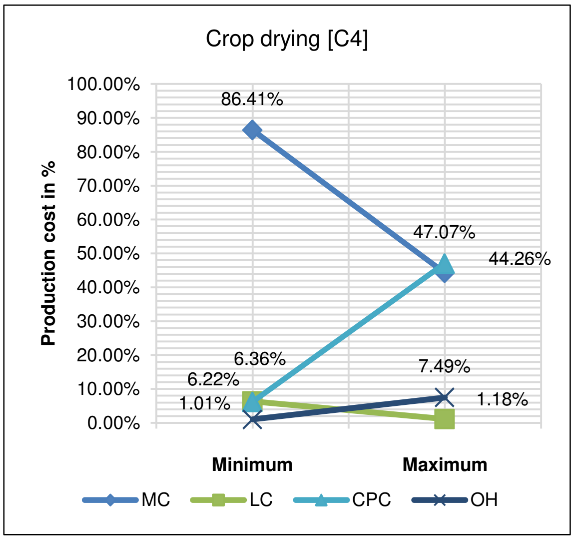


Figure 35 Cost components share on production cost range for concept C3

Figure 36 Cost components share on production cost range for concept C4

As per Figure 35, the material cost contribution is increasing and the labor cost contribution is decreasing from the minimum to the maximum production costs for the bus station. The OPV has the dominance on the material cost for the bus station as shown in the Figure 36. Concept C3 does not require welding process which does not only reduce the contribution of the labor cost but also the capital equipment cost and the overhead cost. Due to high dominance of OPV in the material cost and absence of the welding process for the labor cost, the capital equipment cost and the overhead cost, the material cost contribution is increasing for the maximum production cost for the concept C3.

The result of range of cost components shows that material cost is dominant in all concepts over other cost components. Higher share of capital equipment cost and overhead cost on maximum production cost exists in car parking building and crop drying applications due lower production volume.

5.3 Impact of material costs

The analysis of the material cost results for the contribution of major material items in percentage for all the concepts is demonstrated through the doughnut charts in the Figure 37, Figure 38, Figure 39, Figure 40, Figure 41 and Figure 42. The inner circle of the doughnut chart represents the minimum material cost whereas the outer circle of the doughnut chart represents the maximum material cost.

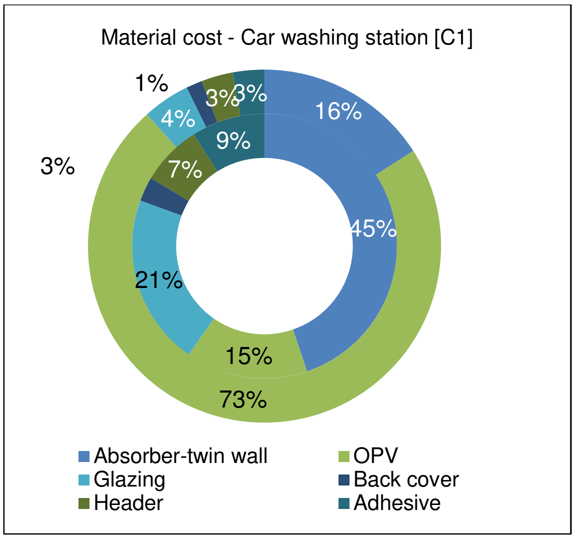


Figure 37 Share of material items on material cost (min – inside, max – outside circle) of concept C1

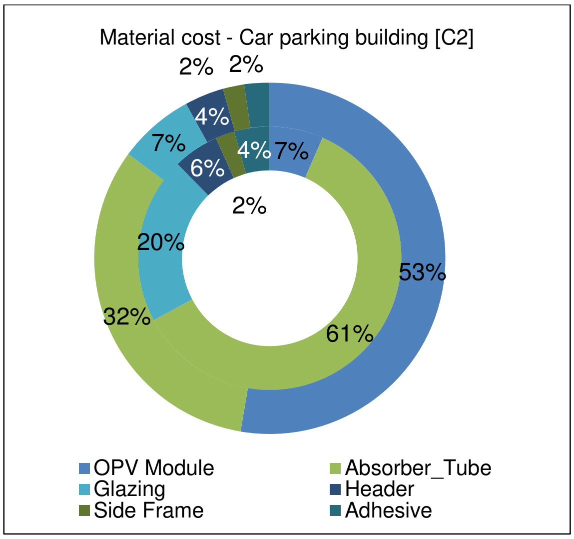


Figure 38 Share of material items on material cost (min – inside, max – outside circle) of concept C2

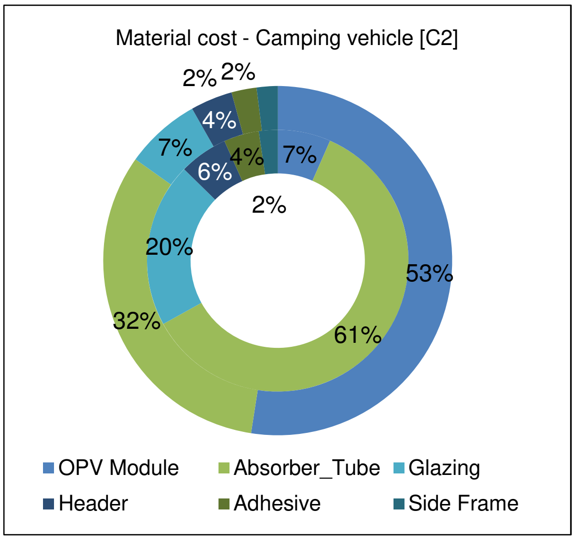


Figure 39 Share of material items on material cost (min – inside, max – outside circle) of concept C2

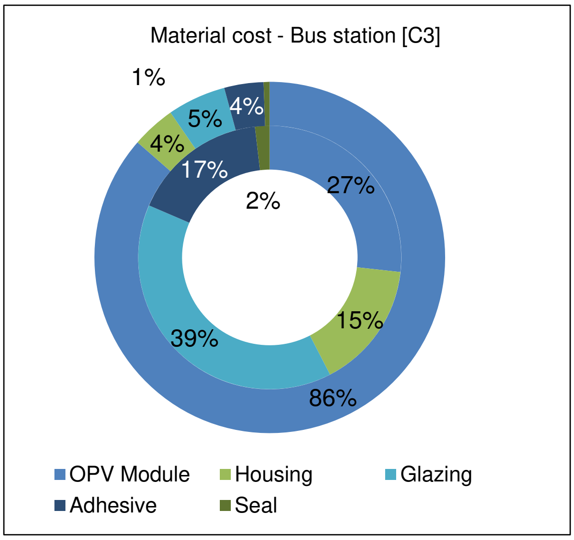


Figure 40 Share of material items on material cost (min – inside, max – outside circle) of concept C3

The material cost of the absorber, the OPV and the glazing are having major share on the total material cost for the respective concepts. The cost of the twin-wall absorber in the concept C1 and C5 are having share of 45% and 40% of the total minimum material cost whereas the cost of tube absorber for the concept C2 is having share of 61% of the total minimum material cost. The share for maximum material cost is reducing by one third for the concept C1 and C5 whereas by half for the concept C2. The glazing has the highest share in the total minimum material cost for the concept C3 as 39% and the concept C4 as 57% of the OPVT air collector. However, the share of glazing for the total maximum material cost is reducing drastically. The share of the material cost of OPV for the total maximum material cost is the highest as 73% for the concept C1, 53% for the concept C2, and 69% for the concept C5. The OPV is having highest dominance in the total maximum material cost for the concept C3 as 86 % and C4 as 80 % for the OPVT air collector.

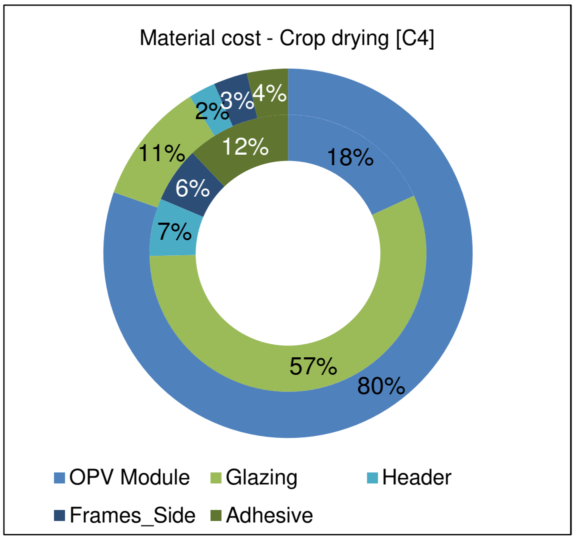


Figure 41 Share of material items on material cost (min – inside, max – outside circle) of concept C4

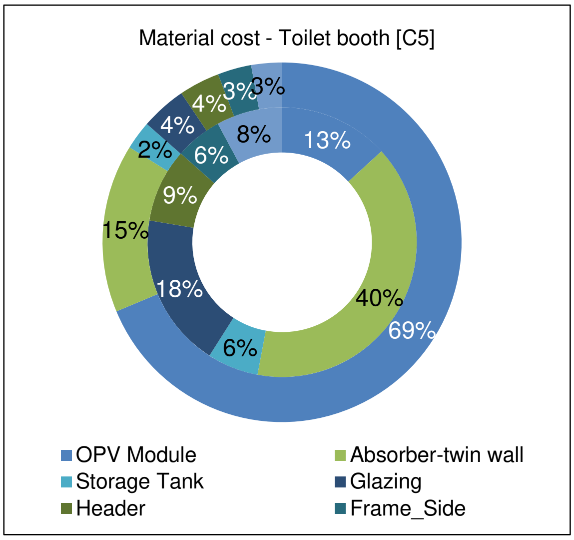


Figure 42 Share of material items on material cost (min – inside, max – outside circle) of concept C5

The impact analysis shows that OPV has high share on material cost for the minimum and the maximum costs. The cost of absorber is high in all water based collector concepts C1, C2, and C5. The cost of OPV is dominant for both air based collector concepts C3 and C4.

5.4 Other cost components

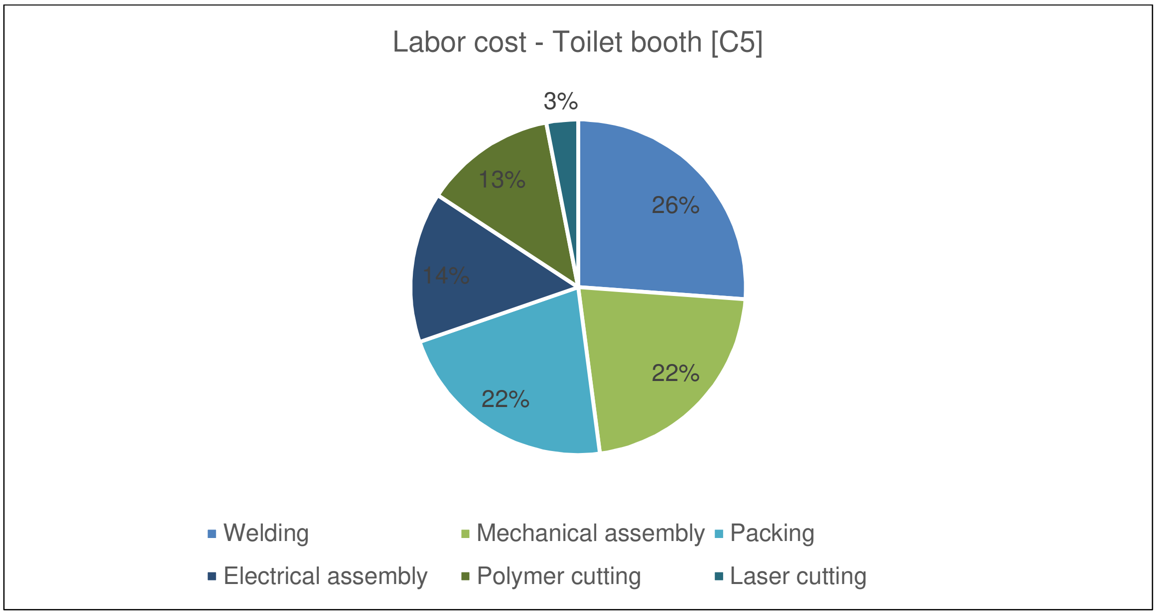


Figure 43 A percentage shares of processes on labor cost for concept C5

The analysis of labor cost for major processes is shown in the Figure 43. The contribution of the labor cost is 42% for the machined operation whereas 58% for the manual operation. The labor cost of welding process is 26% which is 50% of the labor cost for the machined operation.

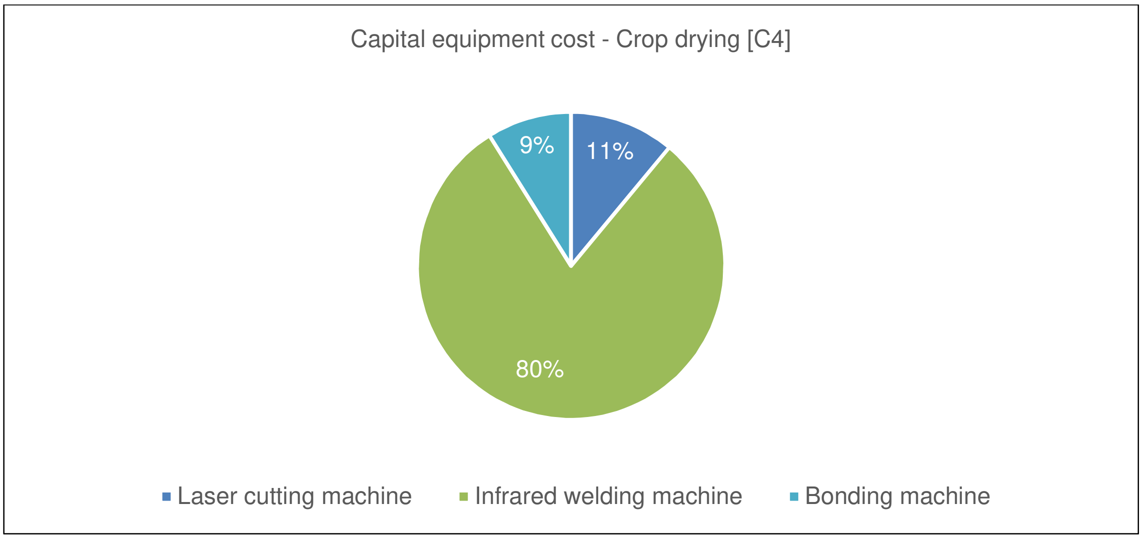


Figure 44 A percentage shares of equipments on capital equipment cost for concept C4

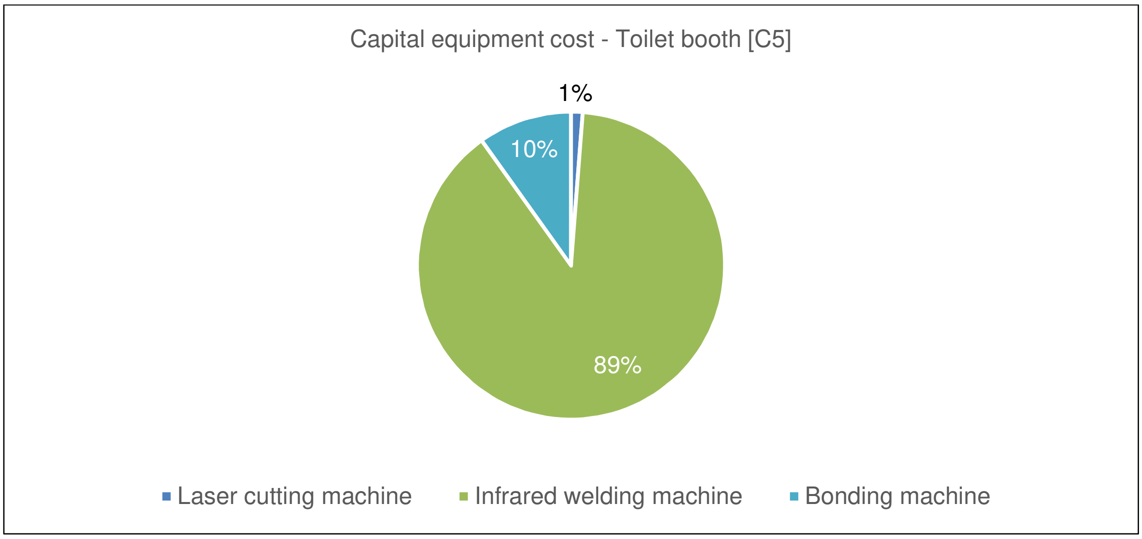


Figure 45 A percentage shares of equipments on capital equipment cost for concept C5

The capital equipment costs for the concept C4 of the crop drying and the concept C5 of the toilet booth applications are analyzed further in the Figure 44 and Figure 45 based on the analysis done for the Figure 36. The share of the infrared welding machine with other major equipment is 80% for the concept C4 and 89 % for the concept C5.

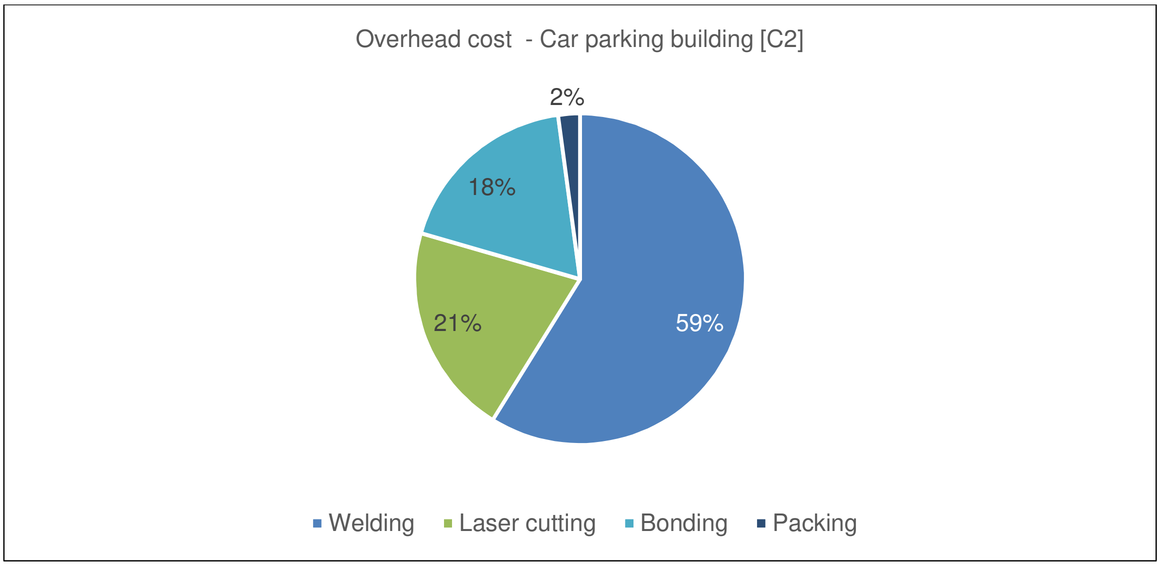


Figure 46 A percentage shares of processes and equipment on overhead cost for concept C2 of the car parking building

The share of the overhead cost for the maximum production cost in the concept C2 of the car parking building application was found as higher as per Figure 33 compared with the overhead costs in all other concepts. The further analysis of the overhead cost for the concept C2 for car parking building is illustrated in the Figure 46. The overhead cost for welding process, area and equipment is 59% of the major contributor of the overhead cost for the concept. The laser cutting and bonding processes have the overhead cost as 21% and 18% respectively. Hence, high investment cost, high energy consumption and high process time of the infrared welding machine as well as the low production volume are the factors for the high overhead cost for the car parking building application.

5.5 Influence of market size

The result of all five scenarios of the market penetrations from the calculation tool are plotted against minimum production cost as per Figure 47. The cost results for all the concepts are nearly constant after the achievement of the 50% of the total market size (highlighted bold data points in Figure 47).

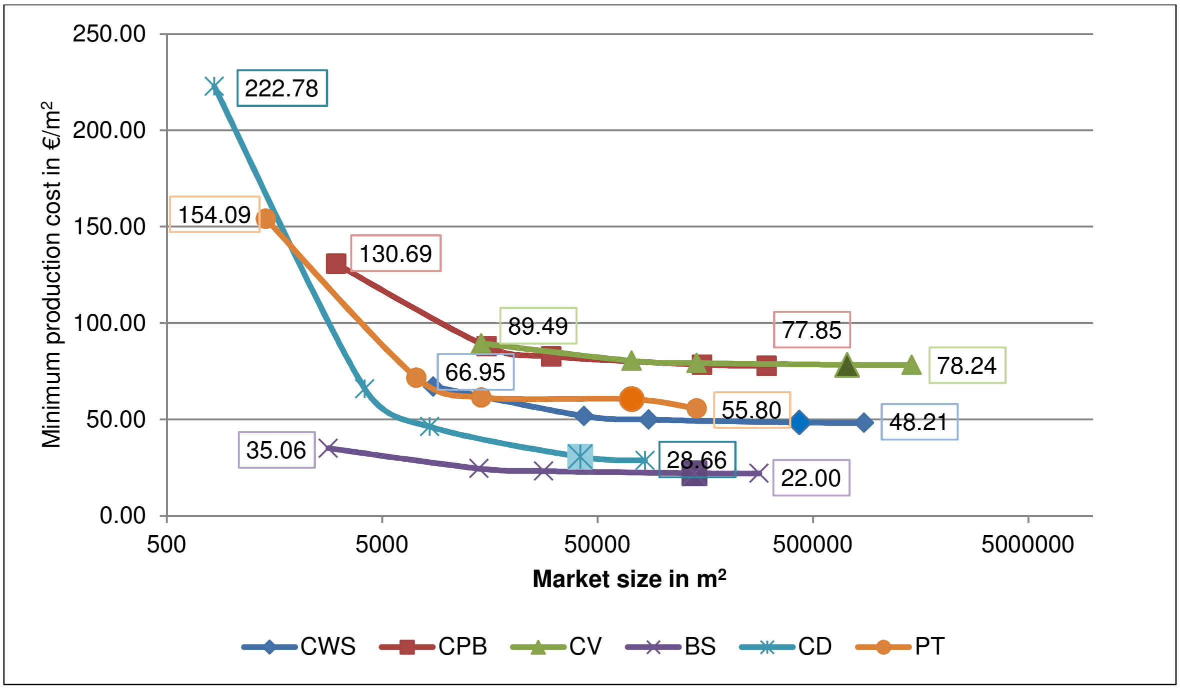


Figure 47 Reduction of the production cost with the increasing market size for all the application concepts

Table 12 Result of market size, production cost, and cost reduction for all market penetration scenarios

Market Penetration			1%	5%	10%	50%	100%
CWS	Market size	m^2	8,640	43,200	86,400	4,32,000	8,64,000
	Production cost	€/m^2	67	51.8	49.9	48.4	48.2
	Cost reduction	%	-	**23**	**2**	**3**	0
CPB	Market size	m^2	3,055	15,275	30,551	1,52,755	3,05,510
	Production cost	€/m^2	130.7	88	82.7	78.4	77.9
	Cost reduction	%	-	**33**	**4**	**3**	0
CV	Market size	m^2	14,400	72,000	1,44,000	7,20,000	14,40,000
	Production cost	€/m^2	89.5	80.4	79.3	78.4	78.2
	Cost reduction	%	-	**10**	**1**	**1**	1
BS	Market size	m^2	2,812	14,062	28,125	1,40,625	2,81,250
	Production cost	€/m^2	35.1	24.5	23.2	22.1	22
	Cost reduction	%	-	**30**	**4**	**3**	0
CD	Market size	m^2	830	4,152	8,304	41,520	83,040
	Production cost	€/m^2	222.8	65.8	46.3	30.6	28.7
	Cost reduction	%	-	**70**	**9**	**7**	1
PT	Market size	m^2	1,440	7,200	14,400	72,000	1,44,000
	Production cost	€/m^2	154.1	71.7	61.4	60.5	55.8
	Cost reduction	%	-	**53**	**7**	**1**	3

Table 12 represents market size and production cost for all five scenarios of market penetration and reduction in production cost with respect to increase in market size. Drastic reduction of the minimum production cost is observed when market size is increasing from 1% to 5% for all the concepts. The percentage reduction is 23%, 33%, 10%, 30%, 70%, and 53% for the concept C1, C2, C2, C3, C4 and C5 respectively. The percentage change in the minimum production cost is less with the increasing market penetration from 5% to 10% as compared with the market penetration from 1% to 5% for all the concepts. The concept C4 and the concept C5 show the highest reduction in the minimum production cost as 9% and 7% respectively while increase in the market penetration from 5% to 10%. The minimum production cost for all the concepts remains nearly constant when moving from the market penetration of 10% to 50%. However, concept C4 is the exception and further reduction in the cost by 7% is achieved. Based on the calculation tool, the maximum cost reduction as 28%, 40%, 13%, 37%, 87% and 64% is possible to achieve with the 100% market penetration for the respective concepts.

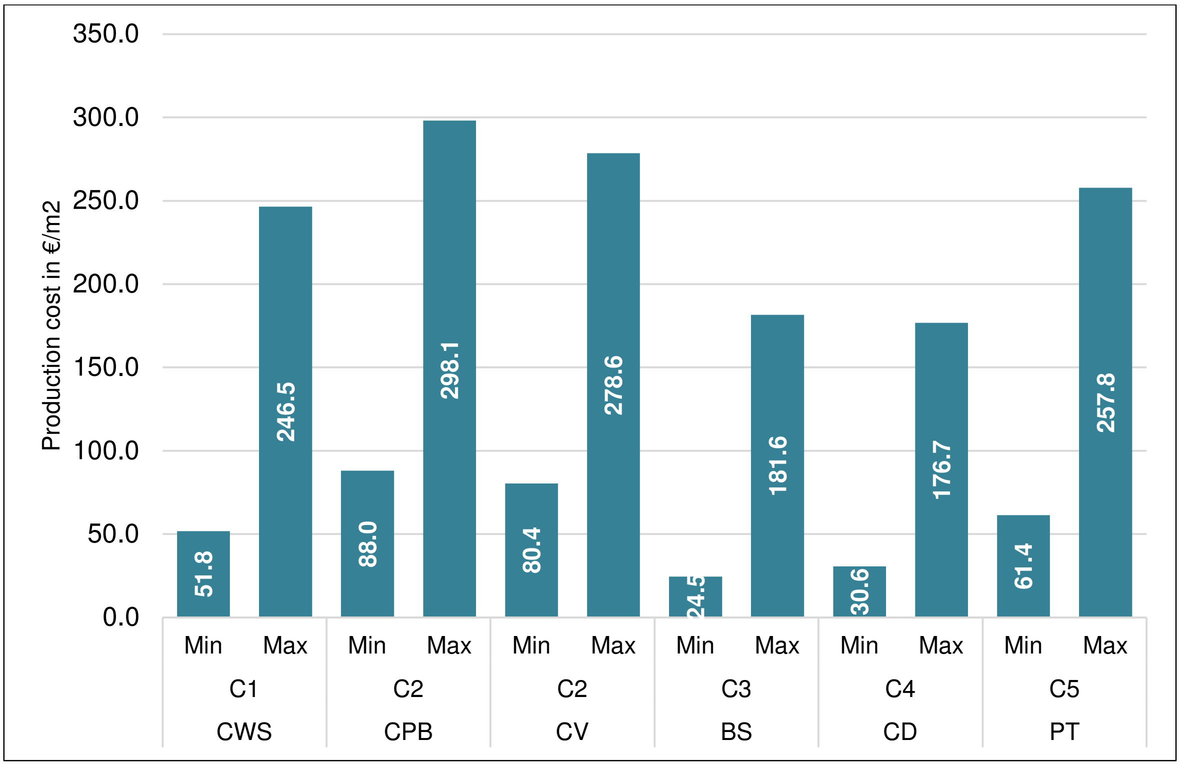


Figure 48 Production cost for optimum market size (5% market penetration) for all concepts

The behavior of change in production cost with reference to increase in market penetration shows that 5% is the optimum market penetration level for the concept C1, C2 and C3, 50% for the concept C4 and 10% for the concept C5. The production cost range for optimum market size is calculated from the tool and result is presented in the Figure 48. The results show that minimum cost of production for optimum market penetration is increasing when compared with production cost calculated for maximum market penetration. It is reversed for the maximum production cost change.

It has been observed that production cost is reducing drastically for small change in market size and becomes constant after optimum market size is captured. The optimum market size is also influencing the minimum and maximum production cost which is to be considered for decision making.

6. Discussion

In this thesis, the production costs for five concepts of six applications were calculated to evaluate their potential for the German market. One concept (C2) is same between two applications but dimensionally different. The analysis of the minimum production cost for all the five market penetration levels reveals to aim for the optimum size of the market instead of 100% of the market size. The minimum production cost becomes nearly constant after the market penetration of 5% for all the concepts except for the concept C4 of the crop drying application is achieved. The minimum production cost becomes nearly constant after 50% of the market penetration for the concept C4. As described in the chapter 4.4.2, the market size is the input as the production volume to the calculation tool. Referring to the equation (IX) and (XII), the production volume has the functional relationship with the two cost components of the production cost, one is the capital equipment cost and the second is the overhead cost. The factors of the capital equipment cost and the overhead cost are reducing with increase in the production volume. However, material cost and labor cost remain unchanged with the increase in the production volume. The constant production cost at higher market penetration is the contribution of the material cost and the labor cost of the respective concepts.

Here, there are two points to be discussed. One is that whether the minimum production cost at optimum market penetration level is to be considered or not. Second is that whether the result of the material cost is to be considered as the minimum cost for all the concepts.

For evaluating the first point, the production cost range is calculated for the optimum production volume. The same numbers of optimum market penetration is fed into the calculation tool to the minimum and the maximum production volume of the respective concepts. Despite the decreasing factor of the capital equipment cost and the overhead cost, the production cost is increasing for the minimum cost and the decreasing for the maximum cost. Therefore, the production cost range at optimum market size is to be considered when the range parameters for material and labor are still elastic. Another important point is that a business reaches to break-even point after optimum market size is captured. So, a business can enjoy more profitable business if optimum market size is the lowest level of market penetration.

For the second point, the dominance of the material cost over production cost is analyzed in the chapter 5.1. It is important to understand the sensitivity of the material costs for major contributing material items, influence of the labor cost, the capital equipment cost and the overhead cost over the production cost before making any decision on the second point. The material items for the OPVT collector concepts are having different characteristics for their respective costs, as per chapter 5.1, the OPV and the absorber are the influencing material items in all the OPVT collector concepts. OPV is still considered as the technological product and it has nearly no commercial market. The OPV is assumed as suitable for the commercial market when 15% efficiency and 15 years of life is achieved. However, the life factor of OPV is not considered in the calculation tool while defining the cost relation for the OPV. The material cost of OPV based on the state of efficiency is to be used in the tool. The twin-wall absorber and the tube absorbers, both are manufactured by plastic extrusion method. The set-up of extrusion requires higher initial investment cost but has the lowest running cost. This characteristics demand for the bulk purchase of the absorber. Additionally, different material types like PP and PPS are used for the absorber and their cost difference per kg is close to 70%. Still the price of the absorber depends on the geographical location of production. Therefore, the absorber costs are sensitive to manufacturing processes, material types and the geographical location of production. These sensitivities are introduced in the calculation tool as the price range for the absorber type instead of independent parameters. The reason for the price range parameter instead of the independent parameter is due to consideration of the B2B business model as described in the chapter 4.3.1. Hence, the input for the price range parameters for the OPV and the absorber must be accurate to get the reliable output of the material cost.

The numbers of the labors are the range parameter for the labor cost in the calculation tool. The minimum labors correspond to the higher level of automation whereas the maximum labors correspond to the conventional manual operations. The influence of the numbers of labors is much less compared with the material cost on the production cost as analyzed in the chapter 5.1 for each concept. However, the processing time for the welding operation for the labor cost is the influencing parameter as seen in the chapter 5.1.

When the production cost is calculated at the optimum production volume then the investment cost of the equipment becomes the sensitive for the production cost. The investment cost is highly dependent on the types of equipment used for the manufacturing processes. Though the industrial expert’s opinion is followed in the selection of the equipment, the alternate less capital-intensive equipment input is possible to explore through the calculation tool. In case of same equipment set-up, the discounting rate and life of the equipment become the influencing parameters for the capital equipment cost. The discounting rate is assumed as the standard 10% for all the equipment. However, the equipment specific discounting rate can be used as the input. The life of the respective equipment is either assumed or referenced from the expert's opinion which can be optimized for respective equipment.

To sum-up, the independent parameters like manual process time, electrical power, discounting rate, life of the equipment are the parameters which can be optimized for more reliable output of the production cost for the OPVT collector concept. Despite the influence of these parameters of the labor cost, capital equipment cost and the overhead cost on the production cost, the material cost dominance is very high. Thus, the material cost calculated from the calculation tool can be considered as the minimum cost possible for the respective OPVT collector concepts.

Moreover, the highest share of OPV and absorber in material cost and material cost as the minimum cost of concept suggest to the manufacturer of the respective items for entering in the OPVT collector business with the least investment in set-up.

From the selected applications and the defined concepts for them, the concept C1 for the car washing station is simple, easy to manufacture and integrate into the application which is reflected as the lowest production cost range among the other water based OPVT collector concepts. The toilet booth, as the standalone application, the thermosiphon based OPVT collector concept is the standardized in size, easy to integrate into the application but complex in manufacturing which is appearing in the contribution of the labor cost and the capital equipment cost. However, the concept C5 for the toilet booth has the higher scaling effect compared to the other water based OPVT collector. The concept C2 for the car parking building and the camping vehicle is the material and the capital-intensive concepts. The concept C3 for the bus station is standardized, easy in manufacturing and in application integration. The concept C3, as the standalone application, is the most suitable for air based OPVT collector. The lowest cost of production and the considerable scaling effects reflect the suitability of the collector for the application. The concept C4 for the crop drying is easy in manufacturing and in application integration but capital-intensive concept. The concept C4 for the crop drying may not be suitable for the Germany as the cultivation of crops happen only for 4-5 months of the year. It means the crop drying of the large volume is necessary in a very limited time. This may become the constraint in capturing the higher market potential in Germany and at the lower market potential this concept C4 has highest production cost.

One of the features of the calculation tool enables the production cost calculation related to the geographical location. It means sourcing price of material items in respective local market, price of the labor, industrial rent and energy rate of location as input to the calculation tool will give production cost of that location. Hence, it is possible to calculate cost for different potential geographies with accurate input data and possible to make decision on potential manufacturing location based on production cost outcome.

The constraint of the tool is the quality of the input data. The calculation tool is sensitive to all range parameters (mainly material item price) which demands for the higher level of accuracy in the input data for reliable output of the production cost.

The production cost per module, numbers of modules per application and the cost of balance of system (BoS) give the production cost per concept. The calculation tool has the provision for the calculation of production cost per concept but the cost of balance of system (BoS) depends on the design of the OPVT collector. For the feasibility stage of the project, the production cost per module and the production cost per square meter of the collector area is sufficient for decision makers. However, the production cost per concept can be the interesting topic for the further research on the calculation tool which will enable the usage of the tool for feasibility stage as well as for the design stage of the product development.

For validating the aim of thesis, it is important to know that investigations of the market potential are made at different stages of the product lifecycle. Basically, the innovators of the product concept investigate the market potential for introducing them into technological market or mass market. When a product is developed and introduced in some market, investors make market potential investigation for entering in the business. Finally, market potential is also estimated when product and business are already existing and owners of the business want to expand their sales volume. Each stage of market investigation definition for potential is changing. The OPVT collector is an innovative concept for the solar thermal industry, the polymer industry and the plastic processing industries. Each industry has its own characteristics of business. The solar thermal industry expects to increase the share of renewable heat with low cost products, polymer and plastic processing industries expect high volume of market with low investment. To match the expectations of all three stakeholders, market potential investigation regarding production cost was to be conducted. In this thesis, potential applications are evaluated for OPVT collector, application based potential of market for Germany is evaluated, potential product concepts are defined, and potential concept having optimum cost of production is calculated by using the calculation tool. At the end, analysis and interpretation of the result reflects the market potential of the OPVT collector which addresses the expectations of all three industries – solar thermal, polymer and plastic processing which reflect as intersection of all three industries on the front-page image of thesis.

7. Conclusion

This thesis has developed a calculation tool to estimate the production cost of the OPVT collector concepts at feasibility stage of the product development. Assessment of the production cost result from the tool with the market size has suggested optimum size of the market at maximized benefit on the production cost. The material cost has been found as the deciding factor for cost of the OPVT collector. Input for the material cost has been assessed as the most sensible parameters in the calculation tool and values of theses inputs must be accurate for most realistic result of the production cost.

In this thesis, six potential applications and five concepts of the OPVT collector have been developed for investigating their market potential for Germany. Car washing application and its flat plate water based collector concept for OPVT has been found as promising for low cost manufacturing and ease in integration. In case of air based OPVT collector, the concept for bus station has been found as the most economical, and easy in manufacturing and application integration.

The tool has been given with the flexibility in considering all the possible distinctions related to technology, material types, geographical location, purchasing, market size and manufacturing set-up as the input. The range parameters in the tool are representing these flexibilities. The comparison of different concepts has been possible with the calculation as it calculates cost per square meter of the collector area. Identification of the independent input parameters for optimization is possible from the assessment of the results from the tool. All independent input parameters, related to infrared welding (investment cost, process time and electrical power) have been identified for optimization as it is the most expensive element of the cost.

To sum-up, the production cost calculation tool is the tangible output of this thesis. It can be used for any geographical location for estimation of its market potential for the OPVT collector. Flexibility in choosing the parameters makes the tool more interactive in decision making. Accuracy and quality of input data is mandatory for reliable results of production cost for the OPVT collector. The production cost of the OPVT collector concept is the material centric. Last but not the least, the OPVT collector business has the potential which will help to overcome the business hurdles of hybrid (PVT) solar thermal collector, OPV, and polymer solar thermal collectors.

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9. Annexures

Annexure 1 Definition of input parameters of the calculation tool

Input Parameter Definition									
Input Parameter			Definition	Possible value	Source of Input data				
Type	Nomenclature				Bill of Material	Industrial Experts	Literature	Web data	Assumption
Pricing factor	a_1		The operator in the calculation of the material items for pricing unit of €/m^2	1, 0					Yes
	a_2		The operator in the calculation of the material items for pricing unit of €/m	1, 0					Yes
	a_3		The operator in the calculation of the material items for pricing unit of €/W_p	1, 0					Yes
	a_4		The operator in the calculation of the material items for pricing unit of €/kg	1, 0					Yes
Sizing factor	l_1		The operator for the relation of length of the item with the Investment cost and the manufacturing process area	1					Yes
	w_1		The operator for the relation of width of the item with the Investment cost and manufacturing process area	1					Yes
Process factor	b_1		The operator in selection of the only automatic processes for the calculation of the process time	1, 0					Yes
	b_2		The operator in selection of the only manual processes for the calculation of the process time	1, 0					Yes
Operational factor	m_1		The operator in the automatic operation of the equipment for the capital equipment cost calculation	1, 0					Yes
	m_2		The operator in the manual operation of the equipment for the capital equipment cost calculation	1, 0					Yes
Repetation Factor	d_1		The operator for the elimination of the repetation of the capital equipments and the processes in the calculation	1, 0					Yes
Maintenance factor	e_1		It is the factor for the maintenance cost of the capital equipments	4%			Yes		
Length	l		It is the length of the material item	0 - 20	Yes				
Width	w		It is the width of the material item	0.025 - 1	Yes				
Height	h		It is the thickness of the adhesive for calculation of the volume of the adhesive per module	0.0002 - 0.0005		Yes			
Quantity	q		It is the number of material item per module for the material and component level manufacturing. It is the number of module for assembly, testing and packing.	1 -	Yes				
Efficiency	η		It is the efficiency of the OPV for calculation of electrical power output.	0.05 - 1.5		Yes			
Irradiation	E		It is the standard solar irradiation for calcuation of the electricial power of the OPV	1000 / location specific		Yes			
Density	ρ		It is the density of the adhesive	1000 - 1500		Yes			
Feed-in speed	V_f		It is the speed of the machine for feeding the material in the automated operation	1.0 - 20.0		Yes		Yes	Yes
Operational Speed	V_o		It is the speed of the machine for respective operation in the automated process	1.0 - 3.0		Yes		Yes	Yes
Manual time	t_{man}		It is the process time required for manual operation for welding and assembly of the collector	5.0 - 10.0		Yes			Yes
Labor price	PH		It is the price paid to the labor of respecitve process	10 / location specific			Yes		
Capital Investment	I		It is the cost of investment for capital equipments used	250 - 900000		Yes			Yes
Discount rate	r		It is the interest rate for calculation of the annual worth of the capital equipment	10% / industry standard			Yes		
Life	T		It is the life of the equipment	10 - 15		Yes			Yes
Main process area	A_m		It is the area of the production including storage	7 - 30				Yes	Yes
Power	P		It is the electrical power of the capital equipment	0 - 15		Yes		Yes	
Energy rate	ER		It is the price of electricity paid by the industry for consumption of one unit	0.15 / location specific				Yes	
Material price unit	PU	**Min.**	It is the minimum price of the material item	0.05 - 15		Yes		Yes	
		Max.	It is the maximum priceof the material item	0.3 - 33		Yes		Yes	
Nos. Of labor	L_n	**Min.**	It is the minimum numbers of labor required for each process	1		Yes			Yes
		Max.	It is the maximum number of labor required for each process	1 - 3		Yes			Yes
Facility rent	FR	**Min.**	It is the minimum rent of the production facility defined for the industrial area	36 / location specific				Yes	
		Max.	It is the maximum rent of the production facility defined for the industrial area	74.4 / location specific				Yes	
Production volume	PV_{module}	**Min.**	It is the minimum production capacity in numbers of modules per year	Application specific					
		Max.	It is the maximum production capacity in numbers of modules per year	Application specific					
	$PV_{unit\ area}$	**Min.**	It is the minimum production capacity in square meter area of module per year	Application specific					
		Max.	It is the maximum production capacity in square meter area of modules per year	Application specific					

Annexure 2 System input datasheet for Car washing station (CWS) concept (C1)

Cost component	Agreegate	Item	Sub-process	Input parameters																																						
				Factors												Independent parameters																	Range parameters									
				Pricing factor				Sizing factor		Process factor		Operational factor		Repetition Factor	Maintenance factor	Length	Width	Height	Quantity	Efficiency	Irradiation	Density	Feed-in speed	Operational Speed	Manual time	Labor price	Capital Investment	Discount rate	Life	Main process area	Power	Energy rate	Material price unit		Nos. Of labor		Facility rent		Production volume			
	Material item / sub-process	i	j	a1	a2	a3	a4	l1	w1	b1	b2	m1	m2	d1	e1	l	w	h	q	η	E	ρ	V_f	V_o	t_{man}	PH	I	r	T	Am	P	ER	PU		Ln		FR		PVunit area		PVmodule	
																																	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
		Nos.		Dimensional less unit											%	m	m	m	nos./module	%	kwh/m2/a	kg/m3	m/min	m/min	min	€/hr	€	%	year	m2	kW	€/kWh	€/unit		nos.		€/m2/a		m2/a		Module/a	
MC	Absorber	1		1	0	0	0									4	0.6		1														15	33								
	OPV	2		0	0	1	0									4	0.3		2	10%	1000												0.05	1.5								
	Glazing	3		1	0	0	0									4	0.6		1														7	9								
	Long frame	4		0	1	0	0									4	0		2														0.8 [4]	2.5 [4]								
	Short frame	5		0	1	0	0									0.6	0		2														0.8	2.5								
	Back cover	6		1	0	0	0									4	0.6		1														1	3								
	Header	7		0	1	0	0									0.6	0		2														5	12								
	Back insulation	8		1	0	0	0									4	0.6		1														2.5	3								
	Side insulation	9		1	0	0	0									4	0.05		2														2.5	3								
	Adhesive	10		0	0	0	1									4	0.6	0.0003				1000											10	20								
	Seal	11		0	1	0	0									20	0		1														0.1	0.3								
LC CP OH	OPV Cutting & Finishing		1					1	1	1	0	1	0	1	4%[1]	4	0.3		2				2	1		10 [2]	100000	10%[1]	10	7	0.4	0.15 [3]			1	2	36 [5]	74.4 [5]	8640	864000	3600	360000
	Absorber Cutting & Finishing		2					1	1	1	0	1	0	1	4%	4	0.6		1				1	3		10	1000	10%	10	7		0.15			1	2	36	74.4	8640	864000	3600	360000
	Glazing Cutting & Finishing		3					1	1	1	0	1	0	0	0	4	0.6		1				1	3		10		1	1			0.15			1	2	36	74.4	8640	864000	3600	360000
	Frame_Long Cutting & Finishing		4					1	1	1	0	1	0	0	0	4	0.05		2				1	3		10		1	1			0.15			1	2	36	74.4	8640	864000	3600	360000
	Frame_Short Cutting & Finishing		5					1	1	1	0	1	0	0	0	6	0.05		2				1	3		10		1	1			0.15			1	2	36	74.4	8640	864000	3600	360000
	Back Cover Cutting & Finishing		6					1	1	1	0	1	0	0	0	4	0.6		1				1	3		10		1	1			0.15			1	2	36	74.4	8640	864000	3600	360000
	Insulation_Back Cutting		7					1	1	1	0	1	0	0	0	4	0.6		1				1	3		10		1	1			0.15			1	2	36	74.4	8640	864000	3600	360000
	Insulation_Side Cutting		8					1	1	1	0	1	0	0	0	4	0.05		2				1	3		10		1	1			0.15			1	2	36	74.4	8640	864000	3600	360000
	End cap and Absorber welding		9					1	1	0	1	1	0	1	4%	0.6	0		1				1	1	9	10	900000	10%	15	30	15	0.15			1	2	36	74.4	8640	864000	3600	360000
	OPV Module and Absorber Bonding		10					1	1	1	0	1	0	1	4%	4	0.3		2				20	1.5		10	100000	10%	15	30	1.5	0.15			1	2	36	74.4	8640	864000	3600	360000
	Frame Assembly		11					1	1	0	1	0	1	1	0	4	0.6		1				1	1	5	10		1	1	7		0.15			1	2	36	74.4	8640	864000	3600	360000
	Insulation Assembly		12					1	1	0	1	0	1	0	0	4	0.6		1				1	1	5	10		1	1			0.15			1	2	36	74.4	8640	864000	3600	360000
	OPVT collector Assembly		13					1	1	0	1	0	1	0	0	4	0.6		1				1	1	5	10		1	1			0.15			1	2	36	74.4	8640	864000	3600	360000
	Glazing Assembly		14					1	1	0	1	0	1	0	0	4	0.6		1				1	1	5	10		1	1			0.15			1	2	36	74.4	8640	864000	3600	360000
	Sealing of OPVT Module		15					1	1	0	1	0	1	0	0	4	0.6		1				1	1	5	10		1	1			0.15			1	2	36	74.4	8640	864000	3600	360000
	Electrical Assembly		16					1	1	0	1	0	1	1	0	4	0.6		1				1	1	10	10		1	1	7		0.15			1	2	36	74.4	8640	864000	3600	360000
	Leak Test		17					1	1	0	1	1	0	1	4%	4	0.6		1				1	1	2	10	250	10%	10	7		0.15			1	1	36	74.4	8640	864000	3600	360000
	Performance Test		18					1	1	0	1	1	0	1	4%	4	0.6		1				1	1	2	10	1000	10%	10	7	1	0.15			1	1	36	74.4	8640	864000	3600	360000
	OPVT Module Packing		19					1	1	0	1	0	1	1	0	4	0.6		1				1	1	10	10		1	1	30		0.15			1	3	36	74.4	8640	864000	3600	360000

Bill of material   Industrial experts   Literature   Web data   Assumption

[1] (Kalowekamo, 2009) ; [2] (Statistics, 2017) ; [3] (Eurostat, 2017) ; [4] (Alibaba, 2017) ; [5] (Colliers, 2017)

Annexure 3 System input datasheet for Car parking building (CPB) concept (C2)

				Input parameters																																						
				Factors												Independent parameters																	Range parameters									
Cost component	Agreegate	Item	Sub-process	Pricing factor				Sizing factor		Process factor		Operational factor		Repetition Factor	Maintenance factor	Length	Width	Height	Quantity	Efficiency	Irradiation	Density	Feed-in speed	Operational Speed	Manual time	Labor price	Capital Investment	Discount rate	Life	Main process area	Power	Energy rate	Material price unit		Nos. Of labor		Facility rent		Production volume			
	Material item / sub-process	i	j	a1	a2	a3	a4	l1	w1	b1	b2	m1	m2	d1	e1	l	w	h	q	η	E	ρ	V_f	V_o	t_{man}	PH	I	r	T	Am	P	ER	PU		Ln		FR		PVunit area		PVmodule	
																																	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
		Nos.		Dimensional less unit											%	m	m	m	nos./module	%	kwh/m2/a	kg/m3	m/min	m/min	min	€/hr	€	%	year	m2	kW	€/kWh	€/unit		nos.		€/m2/a		m2/a		Module/a	
MC	OPV Module	1		0	0	1	0									2.6	0.3		3	10%	1000												0.05	1.5								
	Absorber_Tube	2		0	1	0	0									2.7	0		20														2	4								
	Glazing	3		1	0	0	0									2.6	1		2														7	9								
	Header	4		0	1	0	0									1	0		2														5	12								
	Side Frame	5		0	1	0	0									2.6	0.05		2														0.8[4]	2.5[4]								
	Seal	6		0	1	0	0									7.2	0		1														0.1	0.3								
	Adhesive	7		0	0	0	1									2.6	1	0.0003	1			1000											10	20								
LC CP OH	OPV Cutting & Finishing		1					1	1	1	0	1	0	1	4%[1]	2.6	0.3		3				2	1		10[2]	100000	10%[1]	10	7	0.4	0.15[3]			1	2	36[5]	74.4[5]	3055	305500	1175	117500
	Glazing Cutting & Finishing		2					1	1	1	0	1	0	1	4%	2.6	1		2				1	3		10	1000	10%	10	7		0.15			1	2	36	74.4	3055	305500	1175	117500
	Frame Cutting & Finishing		3					1	1	1	0	1	0	0	0	2.6	0.05		2				1	3		10		1	1			0.15			1	2	36	74.4	3055	305500	1175	117500
	Tube Cutting & Finishing		4					1	1	1	0	1	0	0	0	2.7	0.025		20				1	3		10		1	1			0.15			1	2	36	74.4	3055	305500	1175	117500
	Back Glazing to Headers welding		5					1	1	0	1	1	0	1	4%	1	0		2				1	1	9	10	900000	10%	15	30	15	0.15			1	2	36	74.4	3055	305500	1175	117500
	Back Glazing to OPV bonding		6					1	1	1	0	1	0	1	4%	2.6	0.3		3				12	1.38		10	100000	10%	15	30	1.5	0.15			1	2	36	74.4	3055	305500	1175	117500
	Back Glazing to Tubes Assembly		7					1	1	0	1	0	1	1	0	1	2.6		20				1	1	15	10		1	1	7		0.15			1	2	36	74.4	3055	305500	1175	117500
	Frame Assembly		8					1	1	0	1	0	1	0	0	2.6	0.05		1				1	1	5	10		1	1			0.15			1	2	36	74.4	3055	305500	1175	117500
	Sealing of OPVT Module		9					1	1	0	1	0	1	0	0	2.6	1		1				1	1	5	10		1	1			0.15			1	2	36	74.4	3055	305500	1175	117500
	Electrical Assembly		10					1	1	0	1	0	1	0	0	0	0		1				1	1	10	10		1	1	7		0.15			1	2	36	74.4	3055	305500	1175	117500
	Leak Test		11					1	1	0	1	1	0	1	4%	0	0		1				1	1	2	10	250	10%	10	7		0.15			1	1	36	74.4	3055	305500	1175	117500
	Performance Test		12					1	1	0	1	1	0	1	4%	0	0		1				1	1	2	10	1000	10%	10	7	1	0.15			1	1	36	74.4	3055	305500	1175	117500
	OPVT Module Packing		13					1	1	0	1	0	1	1	0	0	0		1				1	1	10	10		1	1	30		0.15			1	3	36	74.4	3055	305500	1175	117500
	Bill of material		Industrial experts										Literature							Web data					Assumption																	

[1] (Kalowekamo, 2009) ; [2] (Statistics, 2017) ; [3] (Eurostat, 2017) ; [4] (Alibaba, 2017) ; [5] (Colliers, 2017)

Annexure 4 System input datasheet for Camping vehicle (CV) concept (C2)

Cost component	Agreegate	Item	Sub-process	Input parameters																																						
				Factors												Independent parameters																	Range parameters									
				Pricing factor				Sizing factor		Process factor		Operational factor		Repetation Factor	Maintenance factor	Length	Width	Height	Quantity	Efficiency	Irradiation	Density	Feed-in speed	Operational Speed	Manual time	Labor price	Capital Investment	Discount rate	Life	Main process area	Power	Energy rate	Material price unit		Nos. Of labor		Facility rent		Production volume			
	Material item / sub-process	i	j	a1	a2	a3	a4	l1	w1	b1	b2	m1	m2	d1	e1	l	w	h	q	η	E	ρ	V_f	V_o	t_{man}	PH	I	r	T	Am	P	ER	PU		Ln		FR		PVunit area		PVmodule	
																																	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
		Nos.		Dimensional less unit											%	m	m	m	nos./module	%	kwh/m2/a	kg/m3	m/min	m/min	min	€/hr	€	%	year	m2	kW	€/kWh	€/unit		nos.		€/m2/a		m2/a		Module/a	
MC	OPV Module	1		0	0	1	0									2.4	0.3		3	10%	1000												0.05	1.5								
	Absorber_Tube	2		0	1	0	0									2.5	0		20														2	4								
	Glazing	3		1	0	0	0									1	2.4		2														7	9								
	Header	4		0	1	0	0									1	0.05		2														5	12								
	Side Frame	5		0	1	0	0									2.4	0.05		2														0.8 [4]	2.5 [4]								
	Seal	6		0	1	0	0									6.8	0		1														0.1	0.3								
	Adhesive	7		0	0	0	1									1	2.4	0.0003	0			1000											10	20								
LC CP OH	OPV Cutting & Finishing		1					1	1	1	0	1	0	1	4%[1]	2.4	0.3		3				2	1		10 [2]	100000	10%[1]	10	7	0.4	0.15 [3]			1	2	36 [5]	74.4 [5]	14400	1440000	6000	600000
	Glazing Cutting & Finishing		2					1	1	1	0	1	0	1	4%	2.4	1		2				1	3		10	1000	10%	10	7		0.15			1	2	36	74.4	14400	1440000	6000	600000
	Frame Cutting & Finishing		3					1	1	1	0	1	0	0	0	2.4	0.05		2				1	3		10		1	1			0.15			1	2	36	74.4	14400	1440000	6000	600000
	Tube Cutting & Finishing		4					1	1	1	0	1	0	0	0	2.5	0.03		20				1	3		10		1	1			0.15			1	2	36	74.4	14400	1440000	6000	600000
	Back Glazing to Headers welding		5					1	1	0	1	1	0	1	4%	1	0		2				1	1	9	10	900000	10%	15	30	15	0.15			1	2	36	74.4	14400	1440000	6000	600000
	Back Glazing to OPV bonding		6					1	1	1	0	1	0	1	4%	2.4	0.3		3				12	1.38		10	100000	10%	15	30	1.5	0.15			1	2	36	74.4	14400	1440000	6000	600000
	Back Glazing to Tubes Assembly		7					1	1	0	1	0	1	1	0	1	0		20				1	1	15	10		1	1	7		0.15			1	2	36	74.4	14400	1440000	6000	600000
	Frame Assembly		8					1	1	0	1	0	1	0	0	2.4	0.05		1				1	1	5	10		1	1			0.15			1	2	36	74.4	14400	1440000	6000	600000
	Sealing of OPVT Module		9					1	1	0	1	0	1	0	0	2.4	1		7.2				1	1	5	10		1	1			0.15			1	2	36	74.4	14400	1440000	6000	600000
	Electrical Assembly		10					1	1	0	1	0	1	1	0	0	0		1				1	1	10	10		1	1	7		0.15			1	2	36	74.4	14400	1440000	6000	600000
	Leak Test		11					1	1	0	1	1	0	1	4%	0	0		1				1	1	2	10	250	10%	10	7		0.15			1	1	36	74.4	14400	1440000	6000	600000
	Performance Test		12					1	1	0	1	1	0	1	4%	0	0		1				1	1	2	10	1000	10%	10	7	1	0.15			1	1	36	74.4	14400	1440000	6000	600000
	OPVT Module Packing		13					1	1	0	1	0	1	1	0	0	0		1				1	1	10	10		1	1	30		0.15			1	3	36	74.4	14400	1440000	6000	600000
	Bill of material		Industrial experts										Literature							Web data					Assumption																	

[1] (Kalowekamo, 2009) ; [2] (Statistics, 2017) ; [3] (Eurostat, 2017) ; [4] (Alibaba, 2017) ; [5] (Colliers, 2017)

Annexure 5 System input datasheet for Bus station (BS) concept (C3)

Cost component	Agreegate	Item	Sub-process	Input parameters																																						
				Factors												Independent parameters																	Range parameters									
				Pricing factor				Sizing factor		Process factor		Operational factor		Repetation Factor	Maintenance factor	Length	Width	Height	Quantity	Efficiency	Irradiation	Density	Feed-in speed	Operational Speed	Manual time	Labor price	Capital Investment	Discount rate	Life	Main process area	Power	Energy rate	Material price unit		Nos. Of labor		Facility rent		Production volume			
	Material item / sub-process	i	j	a1	a2	a3	a4	l1	w1	b1	b2	m1	m2	d1	e1	l	w	h	q	η	E	ρ	V_f	V_o	t_{man}	PH	I	r	T	Am	P	ER	PU		Ln		FR		PVunit area		PVmodule	
																																	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
		Nos.		Dimensional less unit											%	m	m	m	nos./module	%	kwh/m2/a	kg/m3	m/min	m/min	min	€/hr	€	%	year	m2	kW	€/kWh	€/unit		nos.		€/m2/a		m2/a		Module/a	
MC	OPV Module	1		0	0	1	0									1.5	0.3		4	10%	1000												0.05	1.5								
	Housing	2		0	1	0	0									1.5	1.25		1														3.5	8.4								
	Glazing	3		1	0	0	0									1.5	1.25		1														7	9								
	Adhesive	4		0	0	0	1									1.5	1.25	0.0003	1			1000											10	20								
	Seal	5		0	1	0	0									6	0		1														0.1	0.3								
LC CP OH	OPV Cutting & Finishing		1					1	1	1	0	1	0	1	4%[1]	1.5	0.3		4				2	1		10[2]	100000	10%[1]	10	7	0.4	0.15[3]			1	2	36[5]	74.4[5]	2812	281200	1500	150000
	Glazing Cutting & Finishing		2					1	1	1	0	1	0	0	4%	1.5	1.25		1				1	3		10	1000	10%	10	7		0.15			1	3	36	74.4	2812	281200	1500	150000
	OPV and Glazing bonding		3					1	1	1	0	1	0	1	4%	1.5	0.3		4				9.6	1.92		10	100000	10%	15	30	1.5	0.15			1	2	36	74.4	2812	281200	1500	150000
	Glazing to Housing Assembly		4					1	1	0	1	0	1	1	0	0	0		1				1	1	5	10		1	1	7		0.15			1	2	36	74.4	2812	281200	1500	150000
	Louvers Assembly		5					1	1	0	1	0	1	0	0	0	0		1				1	1	5	10		1	1			0.15			1	2	36	74.4	2812	281200	1500	150000
	Electrical Assembly		6					1	1	0	1	0	1	1	0	0	0		1				1	1	10	10		1	1	7		0.15			1	2	36	74.4	2812	281200	1500	150000
	Sealing of OPVT Module		7					1	1	0	1	0	1	0	0	6	0		1				1	1	5	10		1	1			0.15			1	2	36	74.4	2812	281200	1500	150000
	Performance Test		8					1	1	0	1	1	0	1	4%	0	0		1				1	1	2	10	1000	10%	10	7	1	0.15			1	1	36	74.4	2812	281200	1500	150000
	OPVT Module Packing		9					1	1	0	1	0	1	1	0	0	0		1				1	1	10	10		1	1	30		0.15			1	3	36	74.4	2812	281200	1500	150000

Bill of material · Industrial experts · Literature · Web data · Assumption

[1] (Kalowekamo, 2009) ; [2] (Statistics, 2017) ; [3] (Eurostat, 2017) ; [5] (Colliers, 2017)

Annexure 6 System input datasheet for Crop drying (CD) concept (C4)

Cost component	Agreegate	Item	Sub-process	Input parameters																																						
				Factors												Independent parameters																	Range parameters									
				Pricing factor				Sizing factor		Process factor		Operational factor		Repetation Factor	Maintenance factor	Length	Width	Height	Quantity	Efficiency	Irradiation	Density	Feed-in speed	Operational Speed	Manual time	Labor price	Capital Investment	Discount rate	Life	Main process area	Power	Energy rate	Material price unit		Nos. Of labor		Facility rent		Production volume			
	Material item / sub-process	i	j	a1	a2	a3	a4	l1	w1	b1	b2	m1	m2	d1	e1	l	w	h	q	η	E	ρ	V_f	V_o	t_{man}	PH	I	r	T	Am	P	ER	PU		Ln		FR		PVunit area		PVmodule	
																																	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
		Nos.		Dimensional less unit											%	m	m	m	nos./module	%	kwh/m2/a	kg/m3	m/min	m/min	min	€/hr	€	%	year	m2	kW	€/kWh	€/unit		nos.		€/m2/a		m2/a		Module/a	
MC	OPV Module	1		0	0	1	0									6	0.3		3	10%	1000												0.05	1.5								
	Glazing	2		1	0	0	0									6	1		2														7	9								
	Bracket	3		0	1	0	0									1	0.03		2														5	12								
	Frames_Side	4		0	1	0	0									6	0		2														0.8 [4]	2.5 [4]								
	Adhesive	5		0	0	0	1									6	1	0.0003	1			1000											10	20								
LC CP OH	OPV Cutting & Finishing		1					1	1	1	0	1	0	1	4%[1]	6	0.3		3				2	1		10 [2]	100000	10%[1]	10	7	0.4	0.15 [3]			1	2	36 [5]	74.4 [5]	830	83040	138	13800
	Glazing Cutting & Finishing		2					1	1	1	0	1	0	0	4%	6	1		2				1	3		10	1000	10%	10	7		0.15			1	3	36	74.4	830	83040	138	13800
	Frame Cutting & Finishing		3					1	1	1	0	1	0	0	0	6	0.05		2				1	3		10		1	1			0.15			1	3	36	74.4	830	83040	138	13800
	Glazing to OPV bonding		4					1	1	1	0	1	0	1	4%	6	0.3		3				12	0.6		10	100000	10%	15	30	1.5	0.15			1	2	36	74.4	830	83040	138	13800
	Bracket and Glazing welding		5					1	1	0	1	1	0	1	4%	6	0.05		2				1	1	9	10	900000	10%	15	30	15	0.15			1	2	36	74.4	830	83040	138	13800
	Frame Assembly		6					1	1	0	1	0	1	1	0	0	0		1				1	1	5	10		1	1	7		0.15			1	2	36	74.4	830	83040	138	13800
	Leak Test		7					1	1	0	1	1	0	1	4%	0	0		1				1	1	2	10	250	10%	10	7	0	0.15			1	1	36	74.4	830	83040	138	13800
	Performance Test		8					1	1	0	1	1	0	1	4%	0	0		1				1	1	2	10	1000	10%	10	7	1	0.15			1	1	36	74.4	830	83040	138	13800
	OPVT Module Packing		9					1	1	0	1	0	1	1	0	0	0		1				1	1	10	10		1	1	30		0.15			1	3	36	74.4	830	83040	138	13800
	Bill of material		Industrial experts										Literature							Web data					Assumption																	

[1] (Kalowekamo, 2009) ; [2] (Statistics, 2017) ; [3] (Eurostat, 2017) ; [4] (Alibaba, 2017) ; [5] (Colliers, 2017)

Annexure 7 System input datasheet for Toilet booth (PT) concept (C5)

Cost component	Agreegate	Item	Sub-process	Input parameters																																						
				Factors												Independent parameters																	Range parameters									
				Pricing factor				Sizing factor		Process factor		Operational factor		Repetation Factor	Maintenance factor	Length	Width	Height	Quantity	Efficiency	Irradiation	Density	Feed-in speed	Operational Speed	Manual time	Labor price	Capital Investment	Discount rate	Life	Main process area	Power	Energy rate	Material price unit		Nos. Of labor		Facility rent		Production volume			
	Material item / sub-process	i	j	a1	a2	a3	a4	l1	w1	b1	b2	m1	m2	d1	e1	l	w	h	q	η	E	ρ	V_f	V_o	t_{man}	PH	I	r	T	Am	P	ER	PU		Ln		FR		PVunit area		PVmodule	
																																	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.	Min.	Max.
		Nos.		Dimensional less unit											%	m	m	m	nos./module	%	kwh/m2/a	kg/m3	m/min	m/min	min	€/hr	€	%	year	m2	kW	€/kWh	€/unit		nos.		€/m2/a		m2/a		Module/a	
MC	OPV Module	1		0	0	1	0									1.5	0.3		2	0.1	1000												0.05	1.5								
	Absorber_Profile	2		1	0	0	0									1.5	0.6		1														15	33								
	Storage Tank	3		0	1	0	0									0.6	0.3		1														3.5	8.4								
	Glazing	4		1	0	0	0									1.5	0.6		1														7	9								
	Bracket_Bottom	5		0	1	0	0									0.6	0.06		1														5	12								
	Frame_Side	6		0	1	0	0									1.2	0.06		2														0.8[4]	2.5[4]								
	Adhesive	7		0	0	0	1									1.5	0.6	0.0003				1000											10	20								
	Seal	8		0	1	0	0									4.2	0		1														0.1	0.3								
LC CP OH	OPV Cutting & Finishing		1					1	1	1	0	1	0	1	4%[1]	1.5	0.3		2				2	1		10[2]	10000	10%[1]	10	7	0.4	0.15[3]			1	2	36[5]	74.4[5]	1440	144000	1600	160000
	Absorber Cutting & Finishing		2					1	1	1	0	1	0	1	4%	1.5	0.6		1				1	3		10	1000	10%	10	7		0.15			1	3	36	74.4	1440	144000	1600	160000
	Glazing Cutting & Finishing		3					1	1	1	0	1	0	0	0	1.5	0.6		1				1	3		10		1	1			0.15			1	3	36	74.4	1440	144000	1600	160000
	Frame Cutting & Finishing		4					1	1	1	0	1	0	0	0	1.2	0.06		2				1	3		10		1	1			0.15			1	3	36	74.4	1440	144000	1600	160000
	OPV and Absorber bonding		5					1	1	1	0	1	0	1	4%	1.5	0.3		2				20	4		10	100000	10%	15	30	1.5	0.15			1	2	36	74.4	1440	144000	1600	160000
	Absorber and Bottom Bracket welding		6					1	1	0	1	1	0	1	4%	0	0		1				1	1	9	10	900000	10%	15	30	15	0.15			1	2	36	74.4	1440	144000	1600	160000
	Storage Tank and Absorber welding		7					1	1	0	1	1	0	0	4%	0	0		1				1	1	9	10		1	1		15	0.15			1	2	36	74.4	1440	144000	1600	160000
	Glazing and Absorber Assembly		8					1	1	0	1	0	1	1	0	0	0		0				1	1	5	10		1	1	7		0.15			1	2	36	74.4	1440	144000	1600	160000
	Frame Assembly		9					1	1	0	1	0	1	0	0	0	0		0				1	1	5	10		1	1			0.15			1	2	36	74.4	1440	144000	1600	160000
	Electrical Assembly		10					1	1	0	1	0	1	1	0	0	0		0				1	1	10	10		1	1	7		0.15			1	2	36	74.4	1440	144000	1600	160000
	Sealing of OPVT Module		11					1	1	0	1	0	1	0	0	4.2	0		1				1	1	5	10		1	1			0.15			1	2	36	74.4	1440	144000	1600	160000
	Leak Test		12					1	1	0	1	1	0	1	4%	0	0		0				1	1	2	10	250	10%	10	7	0	0.15			1	1	36	74.4	1440	144000	1600	160000
	Performance Test		13					1	1	0	1	1	0	1	4%	0	0		0				1	1	2	10	1000	10%	10	7	1	0.15			1	1	36	74.4	1440	144000	1600	160000
	OPVT Module Packing		14					1	1	0	1	0	1	1	0	0	0		0				1	1	10	10		1	1	30		0.15			1	3	36	74.4	1440	144000	1600	160000
	Bill of material		Industrial experts										Literature							Web data					Assumption																	

[1] (Kalowekamo, 2009) ; [2] (Statistics, 2017) ; [3] (Eurostat, 2017) ; [4] (Alibaba, 2017) ; [5] (Colliers, 2017)

Declaration in lieu of oath

By

Bhavin Soni

This is to confirm my Master's Thesis was independently composed/authored by myself, using solely the referred sources and support.

I additionally assert that this Thesis has not been part of another examination process.

Place and Date *Signature*