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Life cycle assessment of gravure printed organic photovoltaic solar panels

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In this thesis project, a gate-to-gate comparative life cycle analysis (LCA) was performed on the product under the study is printed organic photovoltaic panels (OPV). Traditional silicon-based solar panels were used as a reference point, i.e. point of comparison. The assessment system boundaries were set for two phases of the products' cycle: manufacturing and use phases, omitting the raw material extraction and production as well as end-of-life phases and possible transportation impacts. The panels were assessed as bare cells, without any additional electronics required to install a solar energy module.

Two main environmental factors were assessed – global warming potential and cumulative energy demand, additionally deriving energy payback time estimates.

Possible avoided CO2 emissions in terms of residential energy use were also estimated in this study. The assessment was done with a perspective of 20 years working time of the panels, which turned out to be a highly important factor in this assessment.

The basics of organic solar energy technologies were discussed, together with the LCA standard guidelines. The study results and conclusion sections provide a discussion on the future development areas for this quite new technology.

Keywords	life cycle assessment, photovoltaics, organic photovoltaics

Contents

List of abbreviations

CED	cumulative energy demand
ETL	electron transport layer
GWP	global warming potential
HTL	hole transport layer
ITO	indium tin oxide
LCA	life cycle assessment
OPV	organic photovoltaics
PCBM	methanofullerene [6,6]-phenyl C_{61}-butyric acid methyl ester
PCE	power conversion efficiency
PEDOT:PSS	poly(3,4-ethylenedioxythiophene)-poly(styrenesulfonate)
PET	polyethylene terephthalate film
PV	photovoltaic
P3HT	poly(3-hexylthiophene-2,5-diyl)
RS	rotary screen printing
R2R	roll-to-roll
ZnO	zinc oxide

1 Introduction

The technological progress is moving fast, together with the amount of energy the world consumes. Everyday life becomes more and more digitized, which raises an issue of the energy demand and its impact on the environment. The question of the cleaner solutions for energy production has been under discussion and development for many years and nowadays becomes more and more important. Solar energy is one of the renewable energy sources and it has an outstanding potential, even though not yet that widely utilized.

The field of photovoltaic energy production has a long history, and throughout the time quite a large amount of development has occurred. Different photovoltaic technologies are used to convert solar energy to the electrical energy. The photovoltaic sector is roughly divided into 3 generations. First generation photovoltaics are presented by the crystalline silicon panels, which account to about 85-90% of the solar market. Thin film technologies represent the second generation (remaining part of the market), and all the novel PV technologies (such as organic photovoltaics) are ranked as the third generation [12].

The solar energy technology represents the clean and environmentally friendly solution for energy production. However, it cannot be considered as an emission free way to produce energy, as the manufacturing process itself implies certain pollution processes. The purpose of this study was to assess the sustainability level of the printed organic photovoltaic solar panels by means of the life cycle assessment technique, with respect to the traditional silicon based solar panels.

The OPVs studied in this thesis are laboratory-scale manufactured panels, produced by the gravure printing technology. This technology implies beneficial product features, such as light weight and freedom of the patterning. Despite this fact, in this thesis project an attempt was made to try and assess the embedded energy as well as emissions, during the OPV manufacturing process, and possible applicability of these panels in a residential use scale.

2 Theoretical background

2.1 Solar Energy Technologies

Energy production based on the solar power utilizes the principle of photovoltaic technique, which allows to produce electrical energy from the sunlight. The photovoltaic energy generation process happens due to the photons that are present in solar spectrum. These particles are exciting the electrons in semiconductor materials, hence allowing a charge to be generated. This is so called a photoelectric effect, which is visualised in Figure 1 below.

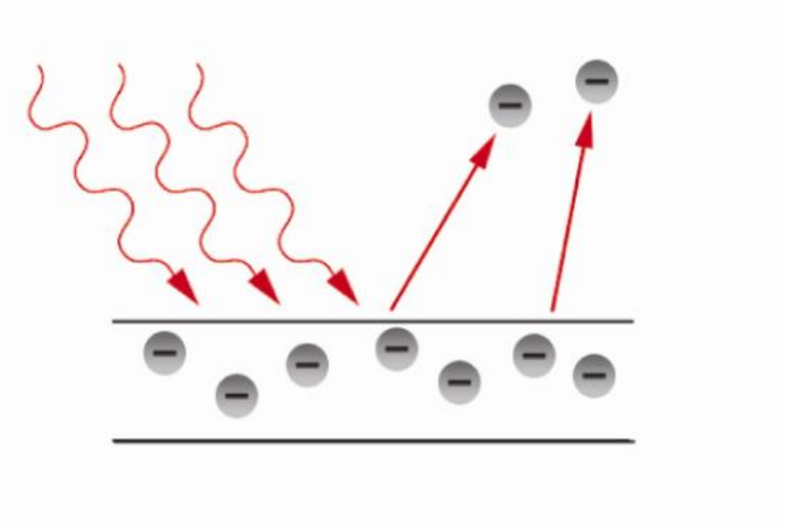

Figure 1: Photoelectric effect [21, p. 2]

The process of energy generation from incident solar light can be roughly divided into four stages [21, p.2]:

1. Absorption of the light by the material
2. Generation of the charge
3. Transfer of the charge
4. Collection of the charge

An incident light, containing the photons, hits the surface of the semiconducting material, which has the electrons being in the ground state. The photons pump up the electrons, and in traditional inorganic solar panels the result of this process is free carriers. In organic photovoltaic panels the process is somewhat different: the electrons do not become free carriers but produce a bound pair of electron and the hole. The efficiency of the OPV depends on the effectiveness of the excitons' dissociation due to the exciton's binding energy [21, p.3]. Further, as the exciton has dissociated, the transportation process is occurring, i.e. moving the dissociated charges towards to the relevant electrode. Finally, the charges are collected from the semiconducting material to the electrodes. This process is represented on the Figure 2 below.

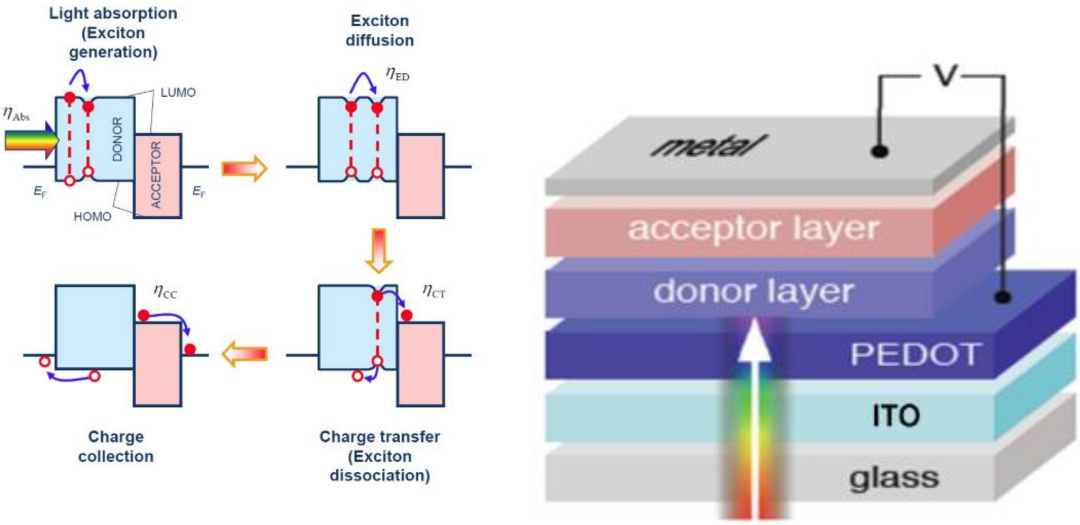

Figure 2: Photovoltaic process [22]

2.2 Organic Photovoltaics and R2R (roll-to-roll) production

It has been mentioned earlier in this work, that OPVs belong to the third generation of photovoltaics. The OPV structure consists of different thin layers, having a photoactive layer placed in between two electrodes. To make the energy generation process work, at least one of the electrodes should be transparent to allow the sunlight to reach the photoactive layer.

The OPV solar cells can be made of three different configurations, as standard, inverted and tandem. The types of the configurations are presented in Figure 4. The photoactive layer is made of mix of the materials, that have both donor and acceptor functions. The morphology (i.e. the arrangement of donor and acceptor materials in the mix) of this layer is the key factor affecting the amount of photocurrent the cell can produce. The working principle of the organic photovoltaic panels is presented on Figure 3.

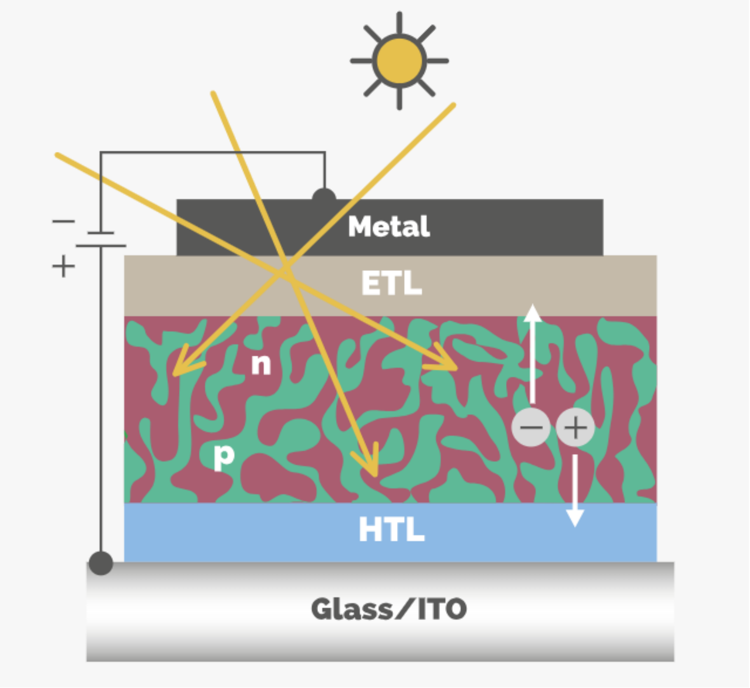

Figure 3: Working principle of the OPV [20]

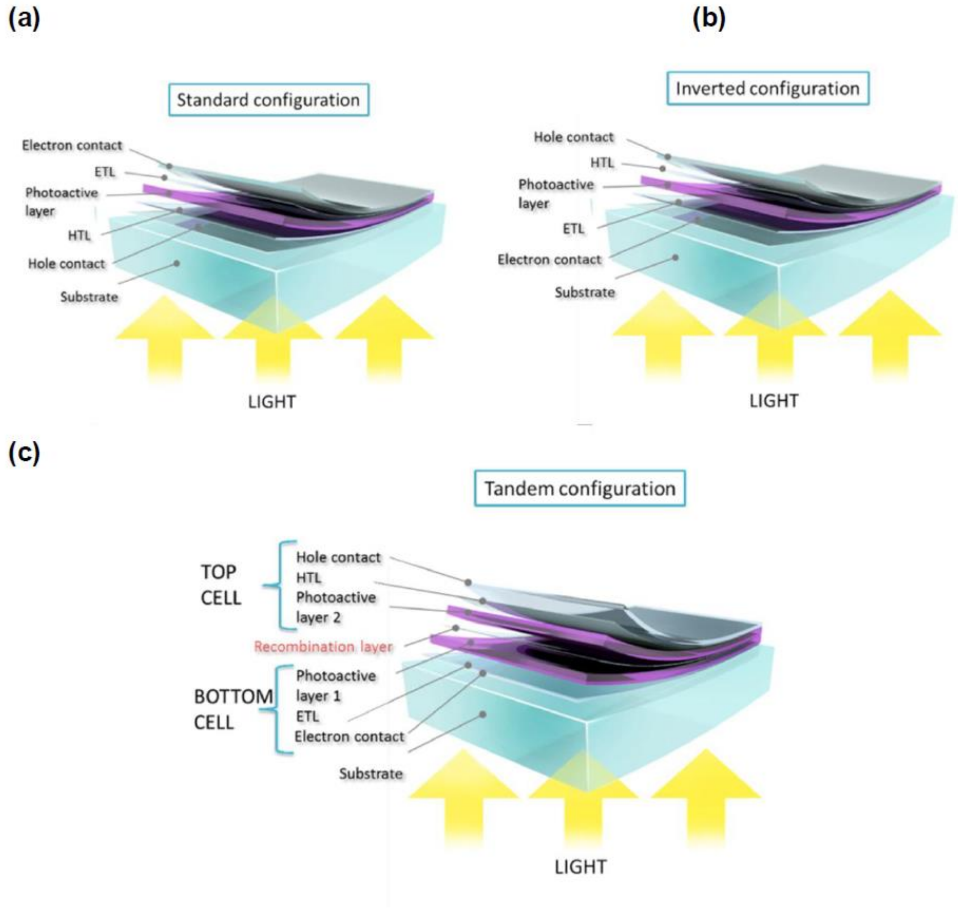

Figure 4: Types of OPV configurations [12, p. 28]

Each configuration includes such layers as a hole contact, an electron contact layer, a hole transport, an electron transport layers, a photoactive layer, and a substrate, that works as a basement of the solar cell. All the layers mentioned are deposited to the substrate in this or that order, using, for example, slot die coating or gravure printing techniques.

The inverted configuration has drawn the researchers' attention over the recent years. Mainly it is a matter of interest due to the possibility to avoid the ETL materials, which can be sensitive to environmental factors, such as moisture or oxygen, and hence reducing the lifetime of the panels. Additionally, this configuration allows the panels to be produced fully by the R2R techniques [12, p. 29].

The examined inverted configuration of the solar panels entails five different layers deposited to the substrate. Each layer has its own function:

Electron contact layer (ITO) - anode - collects charge carriers (electrons). ITO is a conductive oxide, its resistivity is low, but it has high work function and is highly transparent [22].
Electron transport layer (ZnO) - a buffer, later transfers the dissociated electrons towards the anode and is also used to improve the transfer process, i.e. to minimize the energy barrier between layers [12, p. 28]
Photoactive layer (P3HT:PCBM) - absorbs the incoming light, transfers the excitons and holes, after the charge has separated, and is formed from the two semiconductors, electron-donors and electron-acceptor materials [22].
Hole transport layer (PEDOT:PSS) - The advantage of PEDOT:PSS is that it allows to vary its electrical functions by changing the mixing ratios [22].
Hole contact layer (Ag) - cathode - collects photogenerated charge carriers (holes)

The structure of the OPV studied in this thesis is presented on the Figure 5 below.

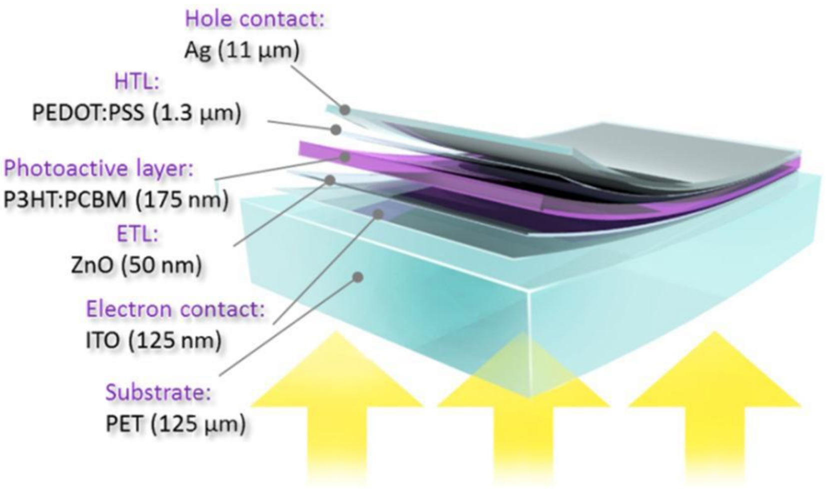

Figure 5: OPV under the study – inverted configuration and layers description [12, p. 45]

The process of the OPV production studied in this thesis has been described in Pälvi Apilo's dissertation *Roll-to-roll printing of organic photovoltaic cells and modules*. First, the ITO is deposited to the substrate with a certain pattern as a negative image. This is done by rotary screen printing. Then, the electron transport layer represented by ZnO is gravure printed onto the substrate and dried at the temperature of about 140 degrees for 30 seconds. The next step is a photoactive layer deposition, which is performed by R2R gravure printing and further drying at 120 degrees for 30 s. After that, the hole transport layer is deposited onto the photoactive layer by rotary screen printing and is dried for 120 seconds at the temperature of 130 degrees. Finally, the hole contact Ag layer is also rotary screen printed and then dried for as long time, as a previous layer. The production process is visualised in Figure 6.

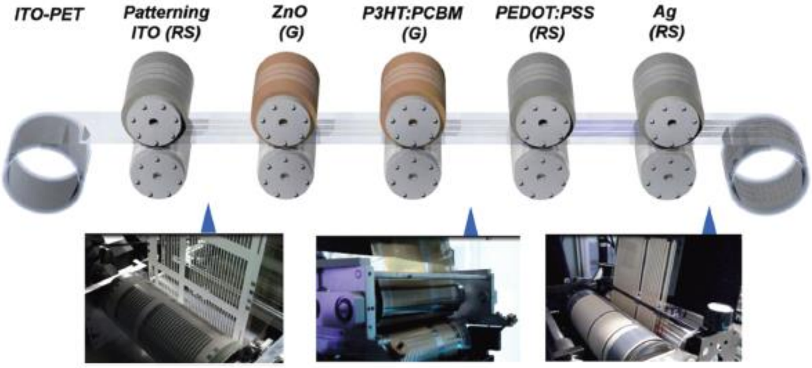

Figure 6: Manufacturing process of OPVs under the study [11, p.2]

Gravure printing is a type of mechanical printing technology and is used to produce a printing matter of high quality and volume. It’s working principle and equipment are rather simple, the speed of the production is high, the process is stable having a high resolution of printing material. Despite its advantages gravure printing has downsides as well, such as the costly price of the cylinders, high demands for process parameters and quality of the substrate surface, which should be very smooth [12]. However, it must be also noted that the latter challenging feature is common also for other mechanical printing methods. The illustration of the working principle is shown in Figure 7.

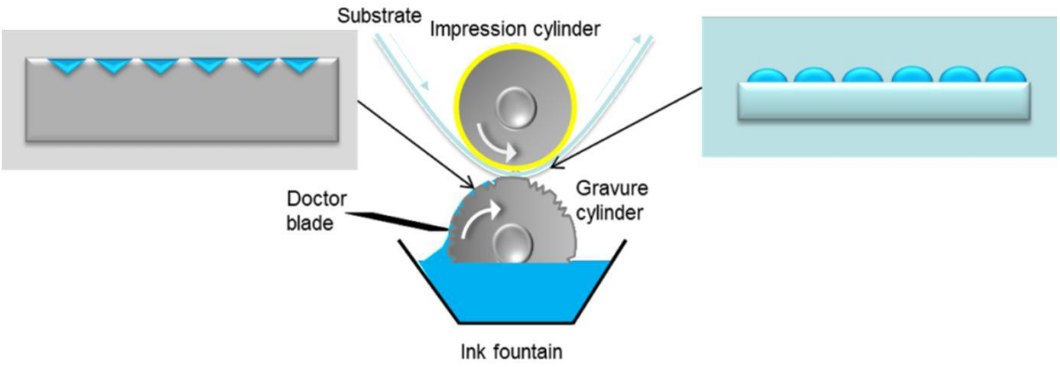

Figure 7: Illustration of gravure printing process [12, p. 32]

Although gravure printing seems to be quite a simple process, there are various factors, that influence the printing process, such as for example cell geometry, substrate type or surface roughness, printing speed and pressure, ink viscosity and rheology, solvents and additives [12, p.32]. However, this technique still enables the freedom of the design patterning, and still is beneficial compared to slot die coating in terms of material use efficiency. The result of the production process is shown in Figure 8.

Figure 8: An example of printed organic solar panels [11, p.6]

3 Methodology

3.1 Life Cycle Assessment

Life cycle assessment (here and further referred as LCA) is a tool that is used to assess the environmental impact of some product or service during its life cycle. The assessment can include different phases of the product's life, starting from the material extraction and ending with the disposal or recycling options.

The application of LCA techniques and results is becoming wider with the growing importance and actuality of sustainability and raising environmental issues. LCA provides an overview to the product's (or service's) stream flows, possibilities for improvement of the environmental footprint and optimization of the industrial processes - which can be utilized in maintaining the product design, or even the whole business strategy of the company. LCA can also help with the eco-labelling, waste management and research and development.

The scope of LCA can vary with the needs and purposes of the analysis, on the basis of which LCA can be divided into several types such as cradle to grave, cradle to gate, cradle to cradle and gate-to-gate. In this thesis project the gate to gate analysis will be performed, omitting the raw material extraction and production phases.

Gate-to-gate analysis: this type of LCA extracts one particular process from the whole life cycle of the product. The gate to gate analyses can be combined with each other, in case it is necessary to assess a certain part of the product life cycle.

The LCA consists of the 4 general phases [24]:

1. Goal and Scope definition
2. Inventory analysis
3. Impact analysis
4. Results interpretation

The possible interconnections in between the phases are illustrated on the figure below.

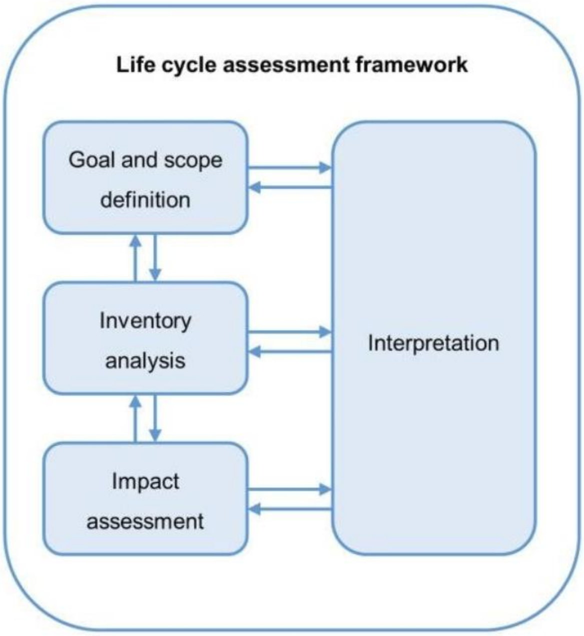

Figure 9: LCA illustration diagram

During the process of LCA, all of the phases are quite tightly interconnected, and the assessment is not done linearly. Quite often the findings require going back to the previous phase in order to correct something.

3.1.1 Goal and scope definition

At the beginning of the assessment the goal and scope of the study shall be clearly defined, naming the reasons and objectives of the work. This phase of the LCA sets up the framework for the analysis, and shall include several important definitions and clarifications (according to the Standard ISO14044-2006 [24]):

- The product system studied, describing the functions of the system
- The functional unit
- System boundaries and limitations
- Allocations
- Methodology and type of impacts under the study
- Assumptions, possible data requirements etc.

3.1.2 Life cycle inventory

The inventory analysis shall be performed based on the directions, limitations and techniques described in the scope definition phase. This phase includes data collection and validation, consequent data relation to the process and functional unit - this also entails possible allocations needed. Further the data is aggregated, and the system boundaries are refined if necessary.

Data collection

Several tools or measures could be performed to assure and collect the relevant and uniform data. It is recommended by the LCA Standard guidelines to draw process flow diagrams, which shall outline processes and interrelations, as well as compile relevant lists of all the flows and units. The process units shall be described with enough amount of details, all the inputs and outputs should be marked, all the affecting factors should be considered.

The data collected can be classified as follows:

- Input data - energy inputs, raw material inputs and other physical inputs.
- Products and waste
- Emission to air, soil and water
- Other aspects

After the data has been processed, it is recommended to perform the sensitivity analysis, to possibly refine the system boundaries.

3.1.3 Life cycle impact analysis (LCIA)

The impact analysis depends on the assessment goals, which define the selection of impact categories. ISO standards establish a certain list of the impact categories, such as global warming, stratospheric ozone depletion, photochemical ozone formation, acidification, nutrient enrichment and ecotoxicity. In this study we would be interested the most on the global warming potential (GWP) and possible energy related categories, such as cumulative energy demand (CED). On the basis of CED, it is also possible to derive energy payback time, which is one of the environmental parameters used to assess solar panels.

Global warming potential entails the rise of the temperature in the atmosphere due to the presence of greenhouse gases. Possible consequences can include melting ices and glaciers, elevated sea level, regional climate changes [25].
Energy categories are described more in the following chapters of this study.

3.2 Life Cycle Assessment of Organic Photovoltaics

Organic photovoltaics is relatively new technology, which has a lot of perspective in the future. The environmental challenges of the modern world are motivating the green technologies to develop more and more of environmentally friendly solutions to reduce or avoid harmful emissions. The traditional photovoltaic technology already poses a clean substitute to the energy production, by using the energy available from the Sun to produce electricity. However, during its lifecycle still some impacts to the environment or human health can happen. Organic photovoltaics bring it to the next level, claiming to reduce their environmental impact.

Life cycle assessment as an environmental management tool is used to provide a numerical basis for the environmental analysis or comparison. As it was mentioned above, this thesis compares printed organic-based photovoltaic technologies developed by VTT to the traditional silicon photovoltaic panels, providing also some comparison data of the traditional fuel production.

The topic is relatively new; hence, not that much of a material is yet available as case studies. Below is a list of the studies that were gathered for the reference and used in this thesis.

- Michael Tsang. Life-cycle assessment of 3rd-generation organic photovoltaic systems: developing a framework for studying the benefits and risks of emerging technologies. 2016 [1]
- Nieves Espinosa Martinez. Organic solar cells: life cycle assessment as a research tool to reduce payback time in environmental impacts. 2012 [2]
- Annick Anctil. Fabrication and life cycle assessment of organic photovoltaics. 2011 [3]
- Kristine Bekkenlund. A Comparative Life Cycle Assessment of PV Solar Systems. 2013 [4]

- Sebasiten Lizin, Steven Van Passel, Ellen De Schepper, Wouter Maes, Laurence Lutsen, Jean Manca and Dirk Vanderzande. Lifecycle cycle analyses of organic photovoltaics: a review. 2013 [5]
- Annick Anctil and Vasilis Fthenakis. Life Cycle Assessment of Organic Photovoltaics. [6]

Some LCA studies on traditional solar panels were utilized in this thesis, such as:

- Nikola Palanov. Life-cycle assessment of Photovoltaic systems – Analysis of environmental impact from the production of PV system including solar panels produced by Gaia Solar. [master thesis] University of Lund. 2014 [14]
- Vasilis Fthenakis, Hyung Chul Kim, Rolf Frischknecht, Marco Raugei, Parikhit Sinha and Matthias Stucki. Life Cycle Inventories and Life Cycle Assessments of Photovoltaic Systems. International Energy Agency. Photovoltaic Power Systems Programme. 2011 [13]
- Khagendra P. Bhandari, Jennifer M. Collier, Randy J. Ellingson, Defne S. Apul. Energy payback time (EPBT) and energy return on energy invested (EROI) of solar photovoltaic systems: A systematic review and meta-analysis. Renewable and Sustainable Energy Reviews. [document on the internet]. 2014 [15]

4 Assessment framework

4.1 Goal and scope definition

The main goal of this thesis is to provide a comparative life cycle and environmental assessment for the printed organic photovoltaics produced by VTT with R2R fabrication technology, in comparison to the traditional silicon solar panels, referring both to the impacts of the traditional fuel use.

4.2 Functional unit and system boundaries

The studies mentioned above mostly use an area unit as a functional unit to avoid the over-complication of the work with such parameters, as cell efficiency, incoming radiation and lifetime, stating that the results achieved could be further converted to other kinds of units (Wp or kWh) if needed. In this study the 1 kWh of energy produced has been used as a functional unit, to make it feasible in terms geographical location and applicable for exact OPVs studied. It also needs to be mentioned, that this functional unit is assumed under the certain conditions of incoming daily solar irradiation, which is iterated and specified later in this study. The point of comparison is the traditional Si-based photovoltaic panels, providing also a reference point of the emission produced by traditional fuel. The lifetime duration of the systems was considered as well, if 20 years would be a lifetime of the traditional Si-based photovoltaic panel and 5 years of lifespan for the OPV under the study.

As for the system boundaries, the steps in the life cycle of OPV could be roughly divided as follows:

- Raw materials extraction
- Raw materials production
- Cell production
- Use phase
- End of life and disposal

In this study the system is limited to the cell production and use phase, which could be classified as gate to gate type of LCA. Several important factors also must be taken into account, such as cell efficiency, possibly efficiency decrease factors, available incoming irradiation. All the possible effects of any transportation types and the module frame production, as well as all the possible additional equipment required for the cells to produce electricity are omitted from the scope of this study.

4.3 Environmental impact assessment categories

The standard guidelines for the LCA provide quite a broad range of the possible environmental impacts to be studied, for instance global warming, stratospheric ozone depletion, acidification, and human toxicity. Each impact category has its own contributors as types of emissions. However, due to the scarcity of the data available and the studies done on this topic, it is generally considered to assess Cumulative Energy Demand (CED) and Energy Payback Time (EPBT, which is not LCA category, but still widely used related to LCA assessments), hence Global warming category, based on the energy consumption data during the manufacturing process. The same approach was applied in this study.

5 Life cycle inventory

The functional unit in this study as mentioned above is 1 kW of energy produced, further compared with a perspective of the 20 years of lifetime. When we compare organic and traditional Si-based solar panels, the production of this amount of energy would depend on several important factors, each of them requires certain assumptions to be made.

5.1 Incoming irradiation available

An average incoming solar irradiation in Finland has been estimated as 980 kW/m2 in Helsinki area annually [8]. However, this study requires a little bit more precise data. Based on the study made by Finnish Meteorological Institute several observations have been made in Helsinki area [9, p. 13]:

Table 1: Average daily measurement of incoming irradiation in Helsinki Area, data extracted from the report of Finnish Meteorological Institute mentioned above [9]

Time period	**Irradiation kWh/m2**
Middle of July	8
August	5.5
Middle of October	2
October - February	1
April	4
Summer peak	8
Average	**4.75**

In a yearly perspective the measurement observations are recorded and illustrated in Figure 10 below.

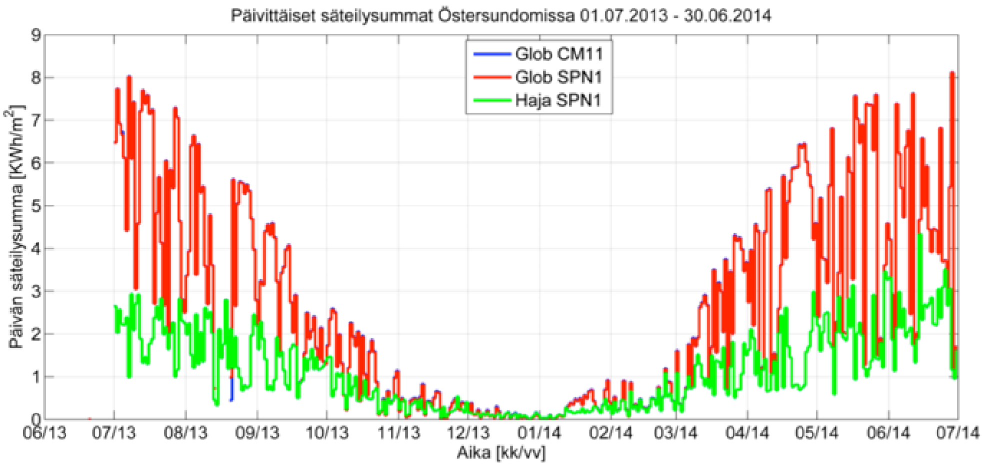

Figure 10: Incoming daily irradiation measurements in the Östersundom area (Helsinki) over a year [9, p. 13]

After the iteration from the data provided by the Finnish Meteorological Institute, we obtain a value of **4.75 kWh/m2** of incoming solar irradiation as an average daily level.

5.2 Solar cell efficiency

An efficiency factor plays important role and basically means, how much energy the cell or the module is going to produce as a power output. Generally, a relation between energy output and cell efficiency could be expressed as follows:

E = A*r*H*PR

where:

E = Energy (kWh)
A = total solar panel area (m^2)
r = solar panel efficiency (%)
H = average incoming solar irradiation
PR = performance ratio (default value 0.75, in general includes possible losses) [7]

The efficiency of the traditional Si-based solar panel can range within 10% and nowadays up to 26% based on the data provided by Solar Cell Efficiency tables, which are updated every 6 months. [10] For this study it has been decided to set an efficiency of a Si-based panels to 20% as an average value.

An efficiency of the printed OPVs used in this study, based on the materials provided by VTT, differs for different samples, therefore it has been advised by the project team to use 3.2% efficiency in the assessment [28].

5.3 Performance ratio

Performance ratio in general defines a solar panel's ability to convert the incoming energy to the usable energy, accounting the possible losses due to different factors.
It is generally assumed, that ground level installations have a performance ratio of 0.85 and rooftop installations - 0.75. If the performance ratio is not specified for certain system, it is normally assumed to use 0.75, which in our case makes sense, as we consider the roof / facade level installations. This value has been set for both traditional Si-based PVs and OPVs.

Once we have assumed and set everything required, we can derive an area of the solar cell needed to produce 1 kWh, which is presented below:

Si-based PV (further referred as PV)	**1.40 m2**
Printed OPV (further referred as OPV)	**8.77 m2**

5.4 VTT OPV manufacturing process

Out of the possible configurations for OPV production the studied modules have been produced as an inverted configuration. The configuration consists of 5 layers, deposited to the ITO-PET substrate. The following manufacturing techniques were used in the process:

Table 2: The manufacturing process of the OPVs, derived based on the reference study [12]

Layer #	Material	Layer function	Manufacturing technique
Layer 1	ITO	Electron contact layer	Patterning by R2R rotary screen printing
Layer 2	ZnO	Electron transport layer	R2R gravure printing
Layer 3	P3HT:PCBM	Photoactive layer	R2R gravure printing
Layer 4	PEDOT-PSS	Hole transport layer	R2R rotary screen printing

Layer 5	Ag	Hole contact layer	R2R rotary screen printing

As mentioned before this study focuses on the energy consumption during the process. The pilot-scale machine used in the manufacturing process is a ROKO R2R printing machine, it has different units, such as gravure printing, flexography and rotary screen printing units. The units can be replaced. [12, p. 42] Based on the data provided by the LIWE Facades project group, the machine has an energy consumption of 0.7 kWh/m and maximum width of the processed surface of 305 mm. Based on this data a necessary length to be printed can be calculated:

- The length of the surface needed to have a 1 m^2 area: 1 m^2 / 0.305m = **3.27 m**

Each step in the production process includes several sub-processes, such as materials preparations, etching or curing, and drying. The printing and drying are the most energy consuming processes, and their speeds vary in gravure printing and rotary screen printing units, hence a power consumption to process the cells of required would be also different, therefore in this study we will consider these two subprocesses. The skeleton of the manufacturing process has been defined in this study as follows:

Step 1. ITO deposition to the substrate
- Rotary screen printing
- Drying

Step 2. ZnO deposition (Electron transport layer)
- Gravure printing
- Drying

Step 3. P3HT:PCBM deposition (Photoactive layer)
- Ink preparation
- Gravure printing
- Drying

Step 4. PEDOT-PSS deposition (Hole transport layer)
- Ink preparation
- Rotary screen printing
- Drying

Step 5. Ag deposition (Electrode)
- Rotary screen printing
- Drying

Step 6. Encapsulation

- Lamination

According to the process description provided in the dissertation about the exact OPV modules under the study, the drying time for steps1, 4 and 5 is about 4 times more, than in steps 2 and 3. The summarized result of the process energy consumption calculation is shown in the table below.

Table 3. Estimated power consumption per each step of OPV production

Step	**Printing speed m/min**	**Printing time (FU), h**	**Drying time, h**	**Power Consumption kWh/m^2**
ITO deposition to the substrate				**0.03**
RS printing	1.1	0.05		0.03468
drying			0.061	0.04239
ZnO deposition (Electron transport layer)				**0.01**
Gravure printing	8	0.01		0.00477
drying			0.008	0.00583
P3HT:PCBM deposition (Photoactive layer)				**0.02**
Ink preparation				0.00656
Gravure printing	8	0.01		0.00477
Drying			0.008	0.00583
PEDOT-PSS deposition (Hole transport layer)				**0.04**
Ink preparation				0.00148
RS printing	2	0.03		0.01908
Drying			0.03	0.02333
Ag deposition (Electrode)				**0.04**
RS printing	2	0.03		0.01908
Drying			0.03	0.02333

Encapsulation				**0.01**
TOTAL				**0.2**

As it can be observed from the table, the most energy consuming processes in the system are PEDOT-PSS and Ag layer deposition, due to the processing speed and drying involved.

The reference point in this assessment is traditional solar panel. On the basis of data published in the report made by International Energy Agency “Life Cycle Inventories and Life Cycle Assessment of Photovoltaic Systems” [13] and the quite extensive LCA study made by Nikola Palanov “Life-cycle assessment of Photovoltaic systems – Analysis of environmental impact from the production of PV system including solar panels produced by Gaia Solar” [14], the manufacturing process energy consumption has been derived. The manufacturing process system can be roughly described as:

Monocrystalline solar cells:
Step 1. Monocrystalline silicon crystal production from solar grade silicon
Step 2. Sawing of monocrystalline silicon wafers
Step 3. Solar cell production
Step 4. PV module production

Multicrystalline solar cells:
Step 1. Multicrystalline silicon ingot production from solar grade silicon
Step 2. Sawing of multicrystalline silicon wafers
Step 3. Solar cell production
Step 4. PV module production

As it can be seen in this system, the steps can be uniformed as crystal or ingot production, sawing of wafers, production of solar cell and consequently of PV module. The energy consumption data per process was extracted from the mentioned work and averaged to one reference value. The data presented in the study in question is assessed for the system of 3 Wp, with surface area of 18.135 m^2, and includes raw material extraction and manufacturing, which is not relevant in our case. Hence, the values were extracted only for the processes mentioned above and allocated per m^2, to make the comparison feasible.

The calculations are presented in the table below.

Table 4. The iteration of estimated power consumption for the traditional PV manufacturing process

PV data	Average (kWh / per 3 kWp system)
Step 1 (crystal / ingot production)	2106
Step 2 (sawing of wafer)	175.14
Step 3 (solar cell production)	572.47
Total:	2853.61
Area of the system (m2)	**Energy consumption (kWh/m^2)**
18.135	**157.4**

With the above provided assumptions and calculations we get a following picture for 1 kWh energy production:

Table 5: Estimated parameters for the functional unit production of both OPV and PV, with estimated embedded power values.

OPV	PV
Incoming Irradiation (kWh/m^2)	
4.75	4.75
Cell Efficiency	
0.032	0.2
Performance ratio	
0.75	0.75
Cell area required (m^2)	
8.77	1.40
Power consumption (kWh/m^2)	
0.2	157.40
Power consumption / FU (kWh)	
1.75	**220.91**

Based on this overview as a first result it can be observed, that there is a vast difference between power consumption of organic photovoltaic solar cells and traditional Si-based solar panels during its manufacturing processes. It is important to remember, that data used for calculation are based on the laboratory scale production, which makes a room for an assumption, that if this process will be developed to the larger scale - allocated values could change.

5.5 Energy Payback Time

There are two most used parameters to estimate an environmental feasibility and performance of the solar cells: energy payback time (EPBT) and energy return on energy invested (EROI). The EPBT is defined as “the length of time a PV system must operate before it recovers the energy invested throughout its lifetime” [15, p. 4]. Which in real means that if, for example, EPBT of PV system is about 5 years with the lifetime of the system of 25 years, then it will produce more or less free of cost energy for about 20 years. If we want to see the feasibility of the energy source in a long-term perspective, EROI would be a parameter to look into. EROI is basically a unitless ratio, which shows how much energy is obtained from an energy source vs. how much energy is required to manufacture and implement the system. The minimum feasibility ratio is considered to be 3:1. If it drops below 1:1 the energy source logically is considered not viable [15, p. 3]. Generally, these parameters are calculated as follows:

EPBT (year) = Embedded energy / annual energy generated by the system
EROI = System lifetime (year) / EPBT (year)

EPBT parameter often includes other relevant factors, such as for example grid efficiency or electrical to primary energy conversion factor, which often depends on the country’s grid and electricity mix. In this study, as the overall comparison is rough due to the limited scope of LCA, this factor has been omitted. It has been assumed, that the lifetime for the PV system would be 20 years, and for OPV - 5. Based on these assumptions and all the earlier calculated data, EPBT and EROI values were obtained and presented in the table below. The parameters are calculated with respect to the functional unit of this study.

	Annual incoming irradiation (kWh/m2)	Annual energy generation (kWh)	**EPBT (years)**	**EROI**
PV	980	206.32	**0.763**	**26.22**
OPV	980	206.32	**0.001**	**5157.89**

The value of these two parameters shows an incredible difference. If we turn EPBT results from years into days, then OPVs will have an energy payback time less than a day, when traditional panels would need about 278 days to produce the amount of energy that equals to the energy consumed over manufacturing phase.

5.6 Energy mix and CO_2 emissions

Different countries utilize different sources of the energy available in their geographical locations, and proportionality of this energy use can be of course also different. The energy mix can include fossil fuels, nuclear energy, renewable energy [17]. The energy mix used by the country thus affects the amount and type of emissions released from the power production.

According to the information provided by Energy Authority of Finland (Energiavirasto), in 2016 energy mix consisted of: 9.13% renewable energy sources, 43.51% nuclear power and 47.36% fossil fuels.

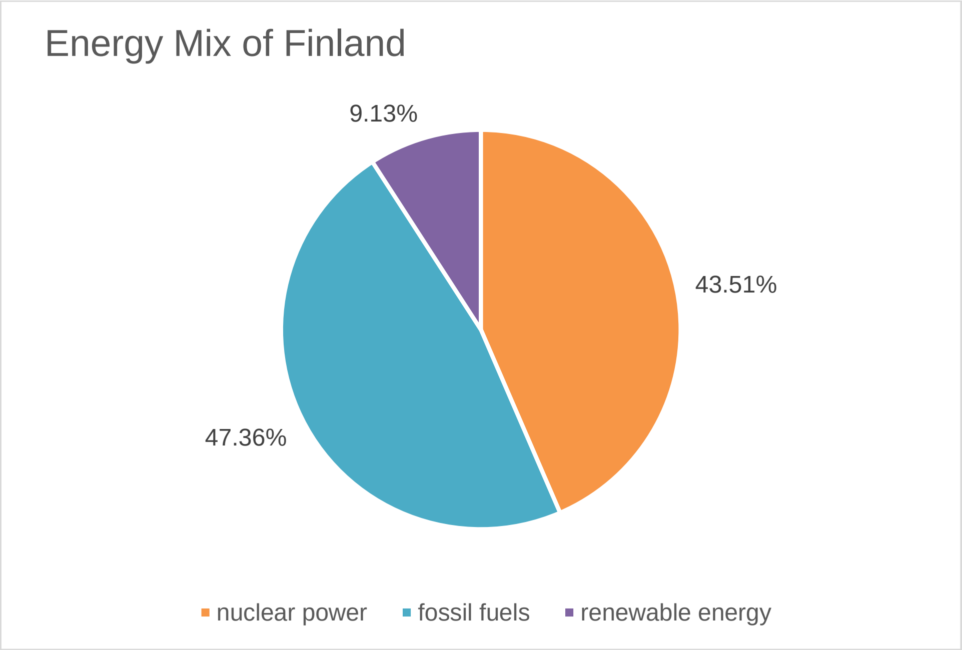

Figure 11: Illustration of Energy Mix of Finland, based on data from 2016

According to the same source, the average amount of CO2 emissions from power production in Finland (according to the energy mix) ranks up to **287.81 g/kWh** [16]. Based on these data we can elaborate CO2 emissions released per functional unit. First, we need to evaluate how much emissions were released during the panels' manufacturing process. For this we allocate the CO2 emission released per kWh of power production, that is needed to manufacture the defined area of the panels.

Table 6: The allocation of associated emissions for the panels' manufacturing process

	Manufacturing CO2 emissions (g/FU area)	**Manufacturing CO2 emissions (g /m2)**
PV	62268.54	44366.34
OPV	494.51	56.37

From the values presented above we can see, that organic photovoltaics absolutely win the competition of being an environmentally friendly solution. However, this comparison is not yet complete, as we should understand how the emissions released over the manufacturing process would allocate per 1 kWh produced over certain period of time. This is where we should use a lifetime factor. The reference point in this study is the traditional solar panel, and its lifetime is assumed to be 20 years. There is no accurate data on the organic photovoltaics under the study, however as a point to start with it has been assumed to use 5 years as a lifetime of the printed OPVs [27]. This means, that all emissions and power consumptions of the OPVs shall be multiplied by 4 to be compared to the traditional photovoltaics. The comparison was calculated in the following table.

Table 7: The comparison of CO2 emissions allocated in terms of 20 years perspective (per FU)

	Lifespan (years)	Manufacturing power consumption / 20 years (kWh)	CO2 emissions from manufacturing process / 20 years (g)	Power production per 20 years (kWh)	**CO2 emissions (g) allocated per kWh produced / over 20 years**
PV	20	220.91	62268.54	4126.32	**15.09**
OPV	5*4	7.02	1978.04	4126.32	**0.48**

Even though at a first glance without any preliminary study the lifetime of the OPVs could seem as a drawback, nevertheless according to our assessment we still see that emission-wise this factor doesn't have a sensible impact. However, in terms of real life usability this still can be seen as an unattractive feature, implying upgrading measures every time its lifespan is expiring.

Furthermore, emissions allocated per square meter in this case similarly favour the organic photovoltaics, as the surface are in case of our functional unit is bigger compared to traditional solar panels.

Table 8: The emissions of CO2 allocated per square meter

	CO2 emissions (g) allocated per kWh produced / over 20 years	Panels Area (FU) (m2)	Yearly CO2 emissions g / m2 (20 years perspective)
PV	15.09	1.40	2218.3
OPV	0.48	8.77	11.3

Iterations done above lead to the thought, that obvious environmental benefits of OPVs enable also small scale or decorative applications, remaining a low impact energy source. Moreover, organic photovoltaics and their manufacturing technology gives an advantage in terms of physical properties, as they are lighter and can be also made flexible and patterned in a different way, which enlarges their application area. Least but not last is the factor of the production scale - the technology studied is of a laboratory scale, which produces an assumption, that if OPVs could be manufactured industrially, the process energy consumption can decrease per unit area, reducing possible environmental impacts.

5.7 Residential power consumption and avoided CO_2 emissions

According to the data provided by the energy company Vattenfall [18] the annual residential energy consumption is growing every year. In Finland the quite a large part of the energy consumed is used for apartment heating, which is normally thermal energy, other needs are lightening, hot water warming, preparing of food and all the electronic and electrical appliances that are used nowadays in modern houses and apartments – in this case an electrical energy is normally being used. The residential heating ranks up to 22% of use of primary energy in Finland [19]. It has been also recently noticed, that summer temperatures in Finland quite often cross the normal levels, hence the cooling need becomes actual during the summer times.

Residential energy consumption has been estimated by Vattenfall and is gathered in the following table. The annual CO_2 emissions were allocated from the emissions release in the energy production process, based on the power consumption of the apartment / house.

Table 9: Annual energy consumption by residential sector and allocated CO_2 emissions

	Annual energy consumption, kWh	Annual CO_2 emissions allocated, kg
Apartment building / 3 persons	2400	676.5
Apartment building / 1 persons	1400	394.6
Row house / 3 persons	4000	1127.5
Row house / 2 persons	3300	930.2
Electrically heated house (detached or row house, 120 m², 4 persons)	18480	5208.9
Detached house (no electrical heating),120 m², 4 persons	7300	2057.7

Assuming, that yearly incoming solar irradiation is about 980 kWh/m2, the power produced from the functional unit per year is going to be about 206.32 kWh. Hence, we can calculate the CO_2 emissions avoided in case of the surface area of the solar panels equals the one we have in our functional unit (for OPVs it was about 8.7 m2).

Table 10: Estimated avoided CO_2 emissions, OPV implemented to facades (FU surface area)

Avoided CO_2 emissions (kg) OPV system implemented	
1 year perspective	5 years perspective
57.7	288.3

The numbers presented above converted to percentages rank to **8.52%** decrease in CO_2 emissions. The room for decrease in emissions also comes from the shading or cooling factor - OPVs in question can be used as a marquee or awning for windows or balconies, which during summer time can help to reduce a cooling energy need, resulting into additional diminishing of the possible impact from residential energy utilization.

6 Results, discussion and sensitivity analysis

The assessment performed above yielded interesting results.

In terms of cumulative energy demand, and within the stage of the solar panel manufacturing process we can see, that the amount of embedded energy related to OPV production is significantly lower compared to traditional solar panels, i.e. about 100 times lower. It is also important to remember two relevant factors related to this comparison: first, the OPVs are produced in our case in laboratory scale pilot-machine, when PVs are produced industrially, second, the uncertainty of the assessment has not been estimated, and data for PV also are extracted from particular LCA study used as a reference. The results are presented in following table.

PV	157.40 kWh / m^2
OPV	0.2 kWh / m^2

At this point of the calculations it also good to check the energy payback time as an environmental category characterizing the feasibility of this or that energy production solution. According to the calculation done in this thesis the following results have been obtained:

Table 11: Energy payback time estimation

	Annual incoming irradiation kWh/m2	E generation annually kWh	EPBT (years)	**EPBT (days)**
PV	980	206.32	0.763	**278**
OPV	980	206.32	0.001	**0.4**

The first results seem to be quite positive, however there are many factors influencing further analysis, that shall be checked. The efficiency of the OPVs is considerably lower than the efficiency of the traditional solar panels. This implies increase in the surface area with respect to our functional unit, causing an increased amount of embedded energy per functional unit. Despite this fact OPVs still remain more environmentally friendly solution.

Table 12: An overview of the CED and GWP values per functional unit assessed

	CED [kWh/m^2]	Surface area of FU [m^2]	PCE	**CED per FU [kWh]**	**GWP [kg CO$_2$ eq.] per FU**
PV	157.40	1.40	0.2	**220.91**	**62.3**

OPV	0.2	8.77	0.032	**1.75**	**494.5**

At this stage of the assessment it can be observed, that OPVs still would be favourable and remain having about 100 times less emissions allocated per functional unit, despite a big difference in a surface area required.

However, the important factor to be considered is a lifetime of the solar panels. Recent studies report, that nowadays traditional solar panels can achieve a life time of about 26 years, opposed to the OPVs that can entail as much as 5 years of lifetime expectancy. Given this point of comparison in our study we assumed a 20 year of lifespan for traditional PVs and 5 years for OPVs. Implementing this factor to our analysis, the results still remain favouring OPVs.

Table 13: An overview of the CED and GWP categories assessed in a 20 years perspective

	Power production / 20 years / FU [kWh]	CED 20 years of operation [kWh]	CO2 emissions from manufacturing per FU / 20 years perspective [kg]	GWP in 20 years of operation [kg CO_2 eq. / kWh]
PV	4126.32	220.91	62.3	0.015
OPV	4126.32	7.02	1.99	0.0048

Based on the above provided results it can be observed, that even though OPVs seem to have major usability drawbacks, they don't influence their environmental impacts, within the borders of our system. However, the sensitivity analysis has been performed in order to see the possible effect coming from the changes in these two parameters.

Table 14: Case 1 – two times increase in efficiency (PCE (OPV) = 6.4%)

	PCE	Surface area of FU [m2]	CED per FU [kWh]	CED 20 years of operation [kWh]	CO_2 emissions from manufacturing per FU / 20 years perspective [kg]	GWP in 20 years of operation [kg CO_2 eq. / kWh]
PV	0.2	1.40	220.91	220.91	62.3	0.015
OPV	0.064	4.39	0.88	3.51	0.99	**0.00024**
OPV ref.	0.032	8.77	1.75	7.02	1.99	0.00048

Table 15: Case 2 – two times increase in lifetime (10 years)

	Lifetime	CED 20 years of operation [kWh]	CO2 emissions from manufacturing per FU / 20 years perspective [kg]	GWP in 20 years of operation [kg CO_2 eq. / kWh]
PV	20	220.91	62.3	0.015

OPV	10	3.51	0.99	0.00024
OPV ref.	5	7.02	1.99	0.00048

From the assessment showed above we can see, that dependences between efficiency and lifetime of the OPVs with respect to the allocated CO_2 emissions are quite linear and result into respective decrease in GWP category of 20 years perspective.

One of the major advantages of the OPV is a larger range of applications. In this study we have considered a possible application of the panels as a window facade in residential objects. Based on the data provided by Vattenfall company we observed, that the integration of the OPV system into the residential energy system could decrease associated CO_2 emissions per about 288.3 kg over the assumed lifetime of the OPV (with surface area equal to our functional unit area). With the improved parameters in a scale of above iterations this value could increase even more.

7 Conclusion

This thesis project was dedicated to LCA analysis of organic-based printed OPVs. The type the analysis performed was gate-to-gate, focusing on the embedded energy of the fabrication process of the cells and the CO2 emissions associated with it. The main object of the study was OPV with a reference point of tradition Si-based panels.

The results showed a vast difference in both categories (CED and GWP) assessed, favouring printed OPVs. Furthermore, the OPVs studied also have such advantages as flexibility and freedom of the patterning, enabling wider range of applications and adding a decorative function on the top of the energy production.

Within the assessment of traditional Si-based panels with respect to printed OPVs, the latter have two drawbacks revealed in the system analysed, which are the lifespan and efficiency. These factors affect the environmental impact of the OPVs, but despite this they remain to be more sustainable solution. However, from the usability point of view, depending on the area of application, this can bring some difficulties or perform as a negative factor for the hypothetical customer.

It must be noted, that quite a lot of development has been done and still goes on in this area. The latest studies report an efficiency reaching **17.3%** for the OPVs of tandem configuration [26]. This development can significantly improve the panels performance, enabling more options for their application.

The research completed in this thesis project has been simplified in several criteria, with the purpose of obtaining a bigger picture and provide a perspective for further development on this topic. It can be suggested to enhance this assessment with more detailed analysis of the production process, which includes more sub-processes, than mentioned in this study. For example, solution preparations or washing can entail certain amounts of energy and includes wider range of chemical used. This leads to another suggestion to enlarge the system boundaries of the study. This change could include the assessment of possible electronic components required for the OPV system to be able to work. On the other hand, the end of life phase (or recycling) could also be added to the analysis, which will provide a wider overview on all the benefits of the organic photovoltaic panels and will allow to assess their impact in more categories, hence perform more detailed analysis.

In terms of residential use assessment, the material inventory can also include possible materials associated with the OPVs implementation to the windows or facades, such as glass and steel structures (frames). The analysis could also be performed with respect to these secondary utilities, to be able to compare an impact of the cells with the impact of other materials used in the system.

Finally, it is strongly suggested to include the efficiency degradation estimation to the assessment. It is known, that traditional Si-based photovoltaics drop efficiency at a rate of 0.5% per year, whereas the OPVs lose their efficiency with about 50% almost immediately or during the first year of use.

With all the proposals and suggestions above, together with the work done in this thesis project it was wonderful to study and proof the environmentally beneficial features of the printed OPV technology. Hopefully this technology will be seen prospering and widely implemented in the nearest future favoring smart design, sustainability and environmental consciousness.

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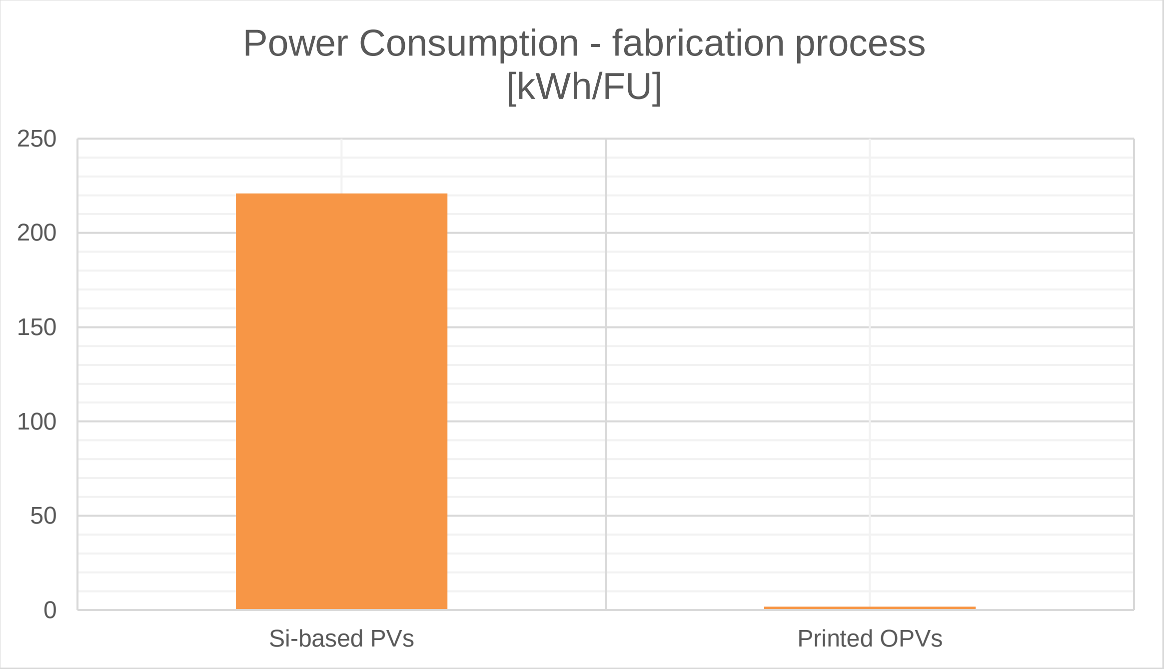
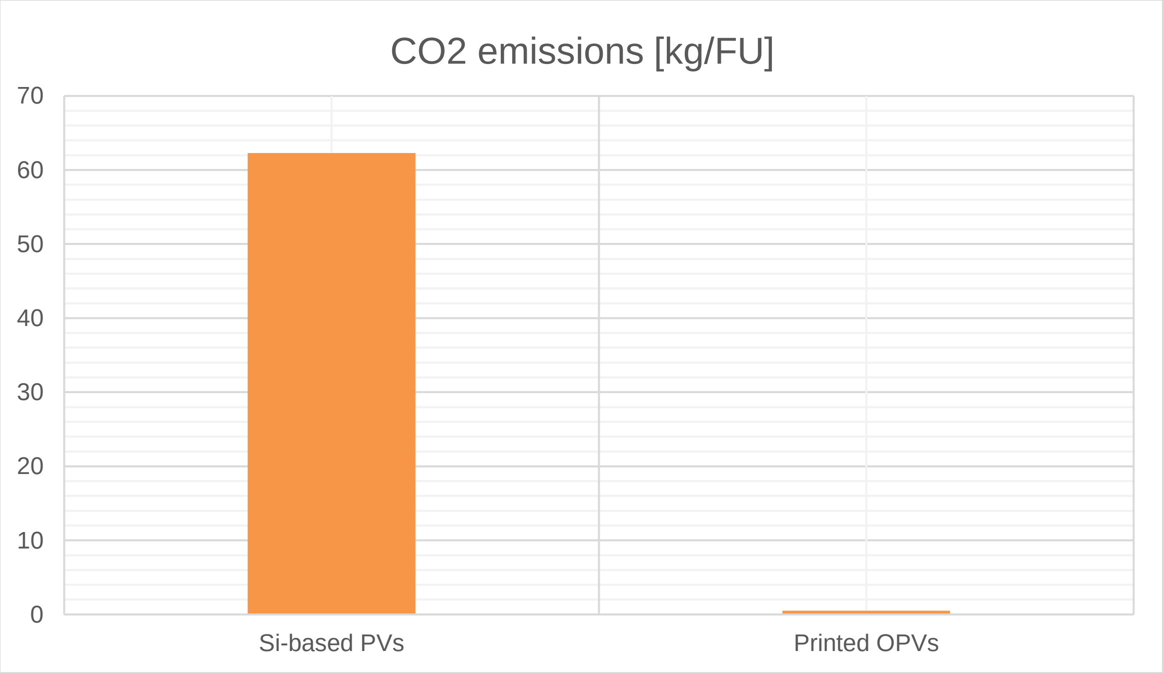
Appendix 1. Graphs and diagrams

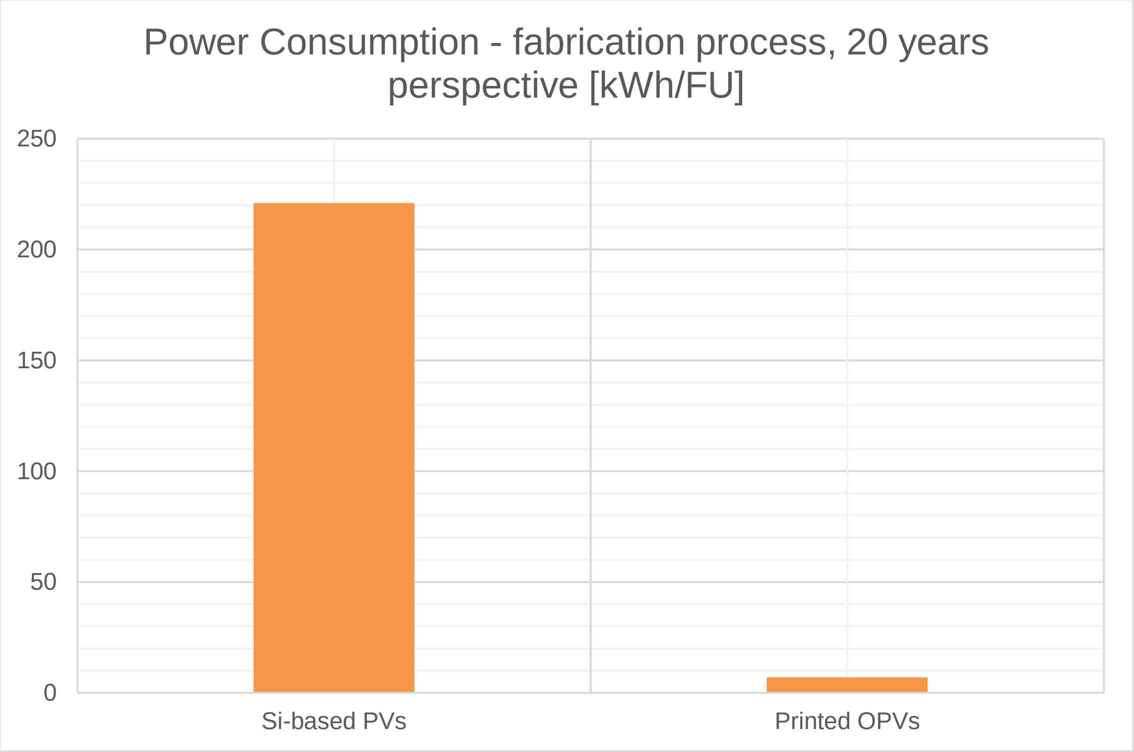
1. Cumulative Energy Demand (per FU)



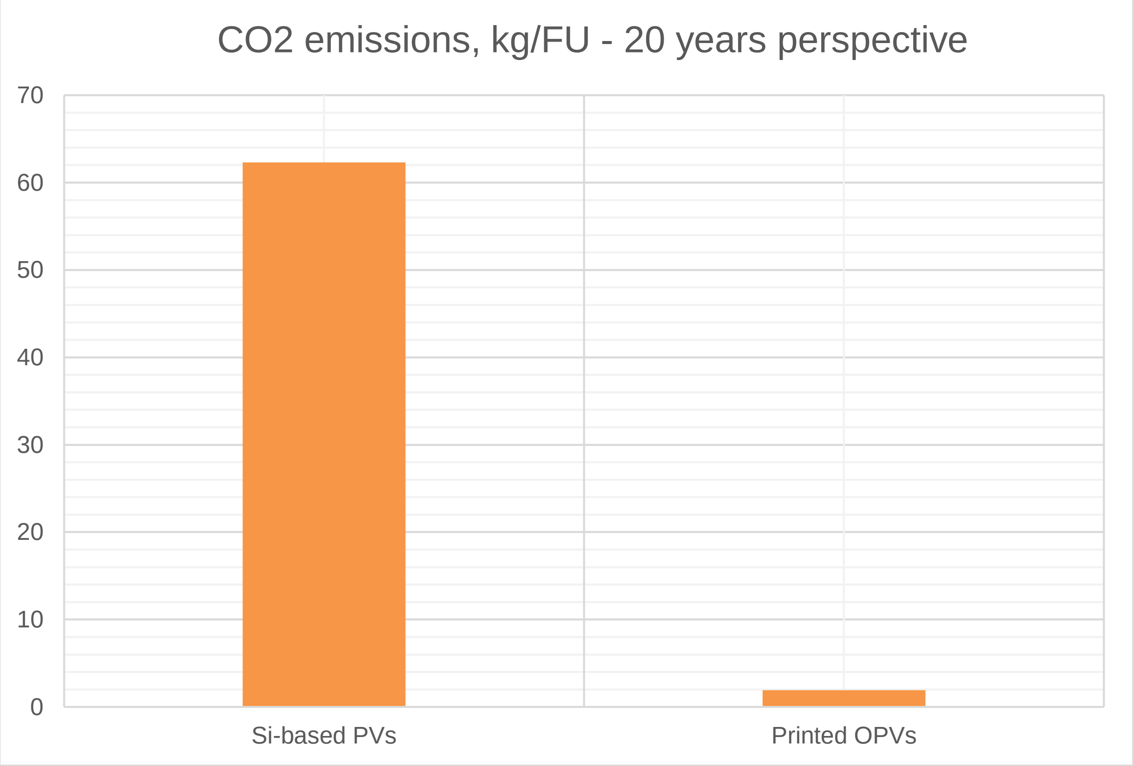
2. CO2 emissions per FU



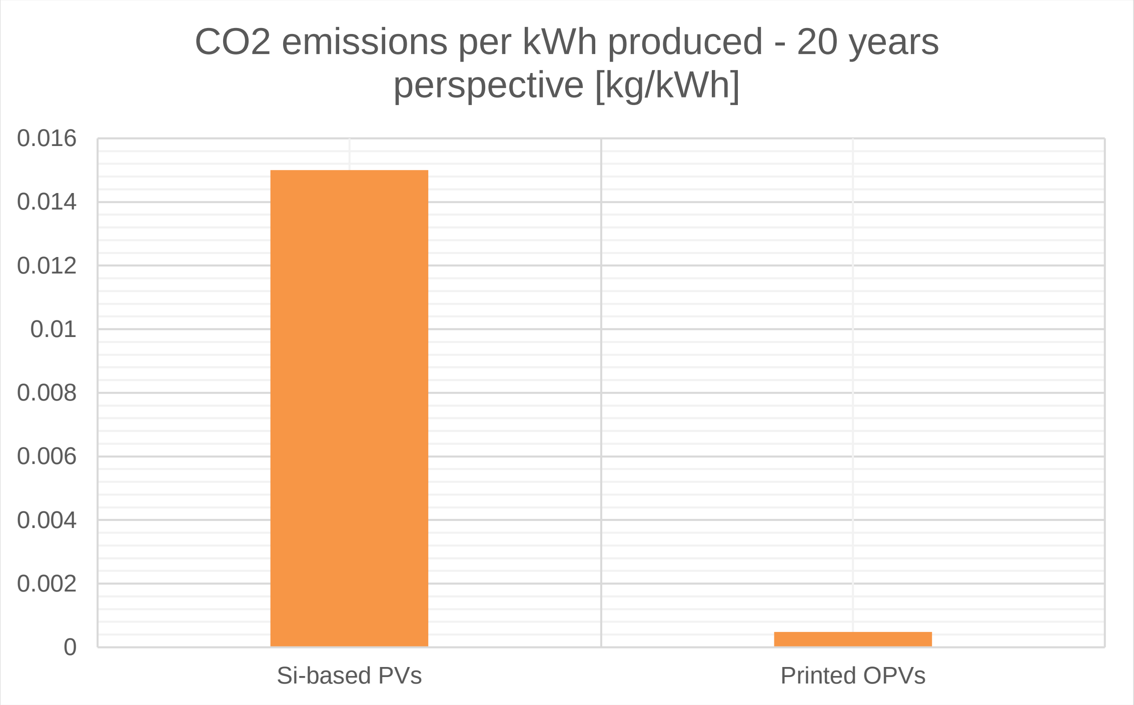
3. Cumulative Energy Demand (per FU) – 20 years perspective



4. CO2 emissions per FU – 20 years perspective



5. CO2 emissions per kWh produced – 20 years perspective



6. Residential Energy Consumption