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Table of Contents

Publishable Executive Summary I
1 Goal and scope definition 1
1.1 Goal 1
1.2 Scope 1
1.2.1 System boundaries 1
1.2.2 Functional unit 1
1.2.3 Methodology 1
2 Inventory analysis 3
2.1 Environmental data 3
2.2 Economic data 6
3 Impact assessment results 6
3.1 Environmental results 6
3.2 Economic results 8
3.3 Uncertainty 8
4 Interpretation and conclusions 9
4.1 Environmental impact 9
4.1.1 Hotspots 9
4.1.2 Changing efficiency 12
4.2 Economic impact 12
4.3 Conclusions 13
Bibliography 14

Publishable Executive Summary

Goal and scope

The environmental and economic impact of the OptiNanoPro self-cleaning coating for OPV cells is investigated following the LCA approach. All life cycle phases from cradle to grave are taken into account, wherever possible based on process data provided by the OptiNanoPro consortium members completed with process descriptions from the Ecoinvent 3 database.

The self-cleaning coating is a PET layer covered with polylactic acid (PLA), silicium dioxide (SiO_2), and polyvinylpyrrolidone (PVP). The purpose of the coating is to increase the hydrophobicity of the OPV cells so that dirt is more easily washed away by rain. This should decrease the light-blocking impact of dirt and therefore increase the average yield of the OPV panels and/or postpone the need for cleaning. The difference in electricity production between coated and uncoated cells was difficult to measure. Therefore, the impact was determined for a range of coating effects: from producing 10% less up to producing 15% more electricity per m².

Environmental impacts are calculated using the IPCC 2013 100a and ReCiPe 2016 (H) endpoint impact assessments methods for determining climate change impacts, damage to ecosystems, damage to human health, and resource depletion. Economic impacts are calculated by economic costs expressed in euros (2018 value).

Results and discussion

The environmental footprint of the OptiNanoPro self-cleaning coating is positive (i.e. associated with environmental benefits) if the coating increases the average electrical yield of the OPV cells by at least 0.5%, see Figure 1. The increase or decrease of electrical production by the self-cleaning layer dominates the environmental impact of the coating. The production impact of the coating is largely dominated by the direct emission of chloroform during electrospraying. Natural gas and crude oil use linked with PET production play an important role in terms of resource depletion for producing the self-cleaning layer.

The total cost of the coating is 19.56 euro per m² for production on industrial scale and waste treatment. The production cost plays an important role in the life-cycle cost of the coating. The coated OPV cells are more profitable than uncoated OPV cells if their electricity yield is at least 12.8% higher than that of the latter, see Figure 2.

Conclusion

It can be concluded that the self-cleaning layer looks promising for improving the environmental impact of OPV cells, especially in case of high-dirt situations, if it can increase the electrical yield of the OPV cells by more than 0.5%. Further research is recommended for reducing the production cost of the self-cleaning coating so that break-even can be reached with lower electricity generation yield improvements.

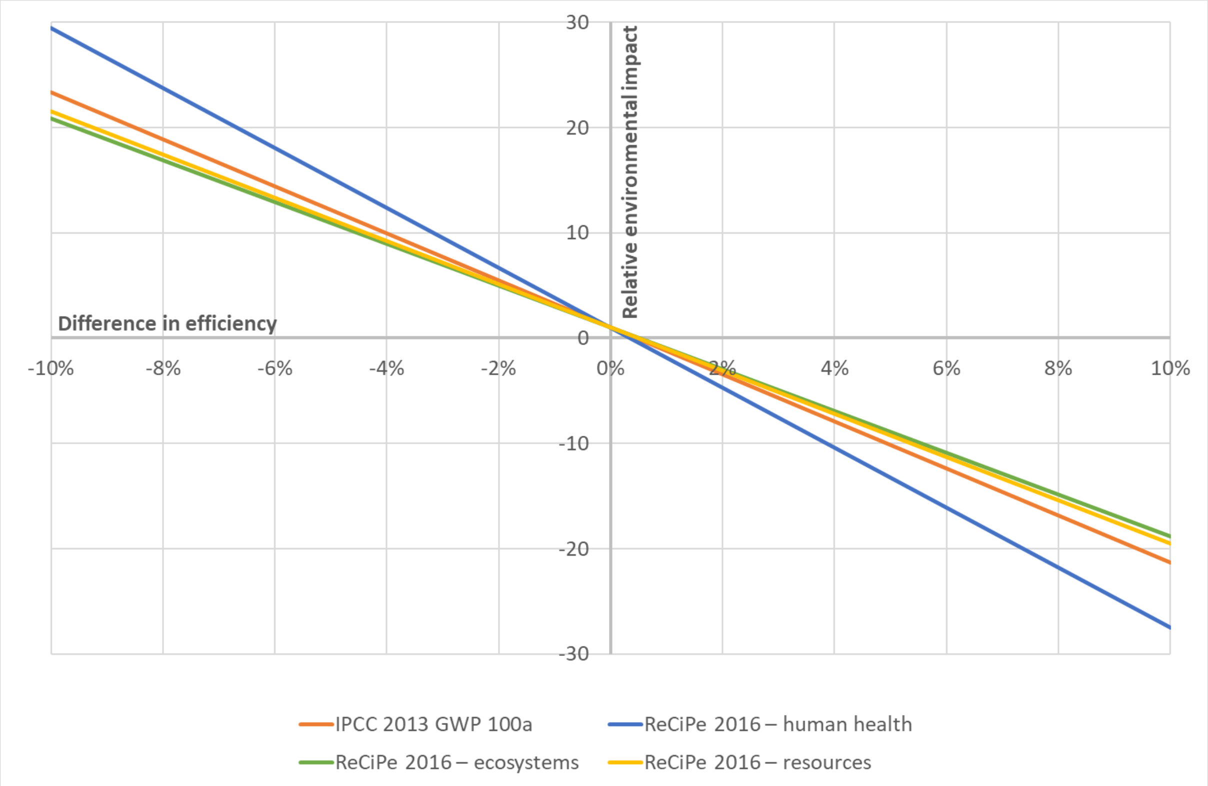

Figure 1: Environmental impact of the OptiNanoPro self-cleaning coating for OPV panels, relative to uncoated cells (/m²)

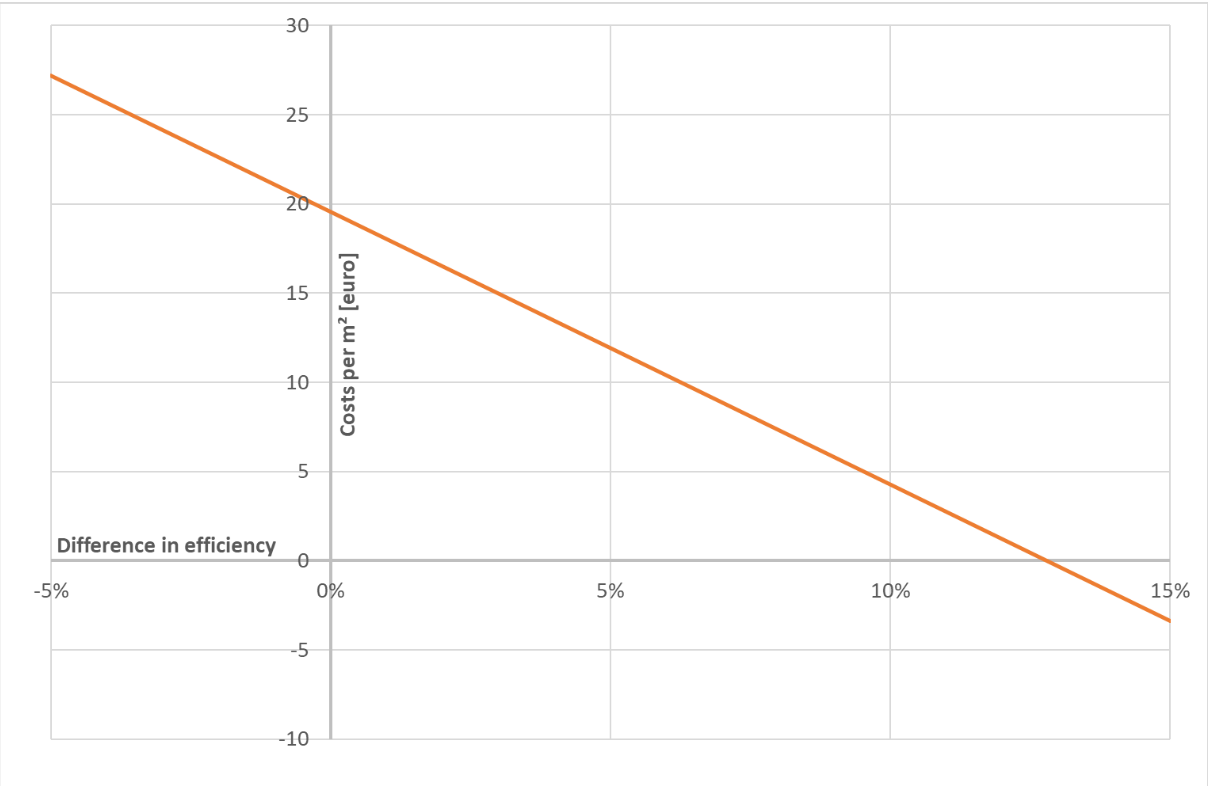

Figure 2: Economic impact of the OptiNanoPro self-cleaning coating for OPV panels, relative to uncoated cells (/m²)

1 Goal and scope definition

1.1 Goal

The goal of this study is to evaluate the environmental and economic sustainability of nano-enhanced organic photovoltaic (OPV) laminates developed during the OptiNanoPro project. These OPV laminates are self-cleaning and are expected to improve the performance of the OPV cells. This report combines the environmental life cycle assessment (e-LCA) and the life cycle cost analysis (LCCA). The total environmental impact and the economic cost are calculated and from these results the hotspots are identified. This allows further improvements on the environmental and economic sustainability of the product. The results are also compared with a standard OPV cell without the nano-enhanced coating.

This deliverable is first of all intended for the partners of the OptiNanoPro consortium and the European Commission which supported this work. Secondly, it is a public report available for anyone interested.

1.2 Scope

1.2.1 System boundaries

A cradle-to-grave approach was used for the production of the nano-enhanced OPV laminate: from natural resource extraction up to waste treatment in the end-of-life phase (Figure 3). Only the effect of the OptiNanoPro coating itself was evaluated. The production of the OPV cells was not taken into account because the focus of this study is the coating and the OPV cells do not differ between the scenario with self-cleaning coating and the reference scenario without self-cleaning coating.

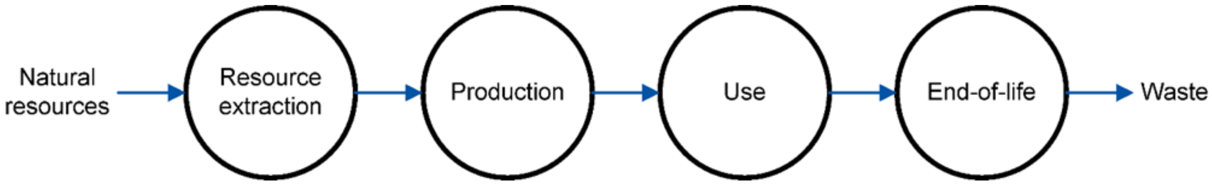

Figure 3:Cradle-to-grave life cycle

1.2.2 Functional unit

The functional unit is the reference to which inputs and outputs are related. This reference is necessary to ensure comparability of the results. It should be easy to interpret by all interested parties and easy to draw practical conclusions from.

The functional unit was chosen to be 1 m^2 of OPV cell surface.

1.2.3 Methodology

Environmental impact

The environmental impact was calculated with SimaPro (version 8.5.2.0) using two impact assessment methods. First of all the impact on climate change was calculated using the IPCC 2013 method (GWP 100a V1.03), the standard and most recent method available. Secondly, the ReCiPe 2016 endpoint method (hierarchic) was used to calculate the results in three endpoint categories: damage to human health, damage to ecosystems, and depletion of resources. In the next paragraphs a brief introduction to these two methods is provided.

Changes in atmospheric concentrations of greenhouse gases (GHGs) and aerosols, land cover and solar radiation alter the balance of the climate system. This leads to the warming of the climate system which is proven by observations of increases in global air and ocean temperatures, the rising of the global average sea level and the melting of snow and ice. This has an impact on water, weather, ecosystems, food production, coastlines, health, tourism, infrastructure, etc. [1] The standard method for measuring climate change in LCAs is the baseline model of 100 years of the International Panel of Climate Change (IPCC). Although the time frame of 100 years is adopted as basis, also impact over 20 years or over 500 years can be calculated [2]. GHGs have different radiative properties and lifetimes. Therefore they have a different warming influence (radiative forcing) on the global climate system. In order to compare the warming influences of all GHGs, a common metric is implemented where the radiative forcing of CO_2 is used as the reference. The equivalent CO_2 emission of a GHG is the amount of CO_2 emission that would cause the same time-integrated radiative forcing, over a given time horizon. This is obtained by multiplying the emission of a GHG by its Global Warming Potential (GWP) [1].

At the endpoint level, the environmental impact is expressed in each of the three main categories: damage to human health, damage to ecosystem diversity, and damage to resource availability. The damage to human health is calculated using the concept of disability adjusted life years (DALY). It is based on human health statistics and is the sum of years of life lost and years of life (partially) disabled. It is assumed that every year lost is equal for all ages and possible future damage is disregarded. For ecosystems this method assumes that the diversity of species adequately represents the quality of ecosystems. The indicator that is used is the loss of species during a certain time in a certain area, expressed as the potentially disappeared fraction of species (PDF, in species.year). In this method all species are considered equally important. The indicator is the sum of the effect for terrestrial, freshwater and marine water systems, taking into account the species density. For resource depletion the model is based on the geological distribution of mineral and fossil resources and assesses how the use of these resources causes marginal changes in the efforts to extract future resources (in USD2013). For minerals this means that the average grade of the ore declines. For fossil fuels this means that also less conventional fuels need to be exploited to meet the demands. The basis is the cost increase of extraction due to effects that result from continuous extraction. This is multiplied by a factor that expresses the amount consumed. These three categories are the result of a weighted sum of the ReCiPe midpoint results [3]. An overview of the conversion from data inventory to midpoint and endpoint results is given in Figure 4.

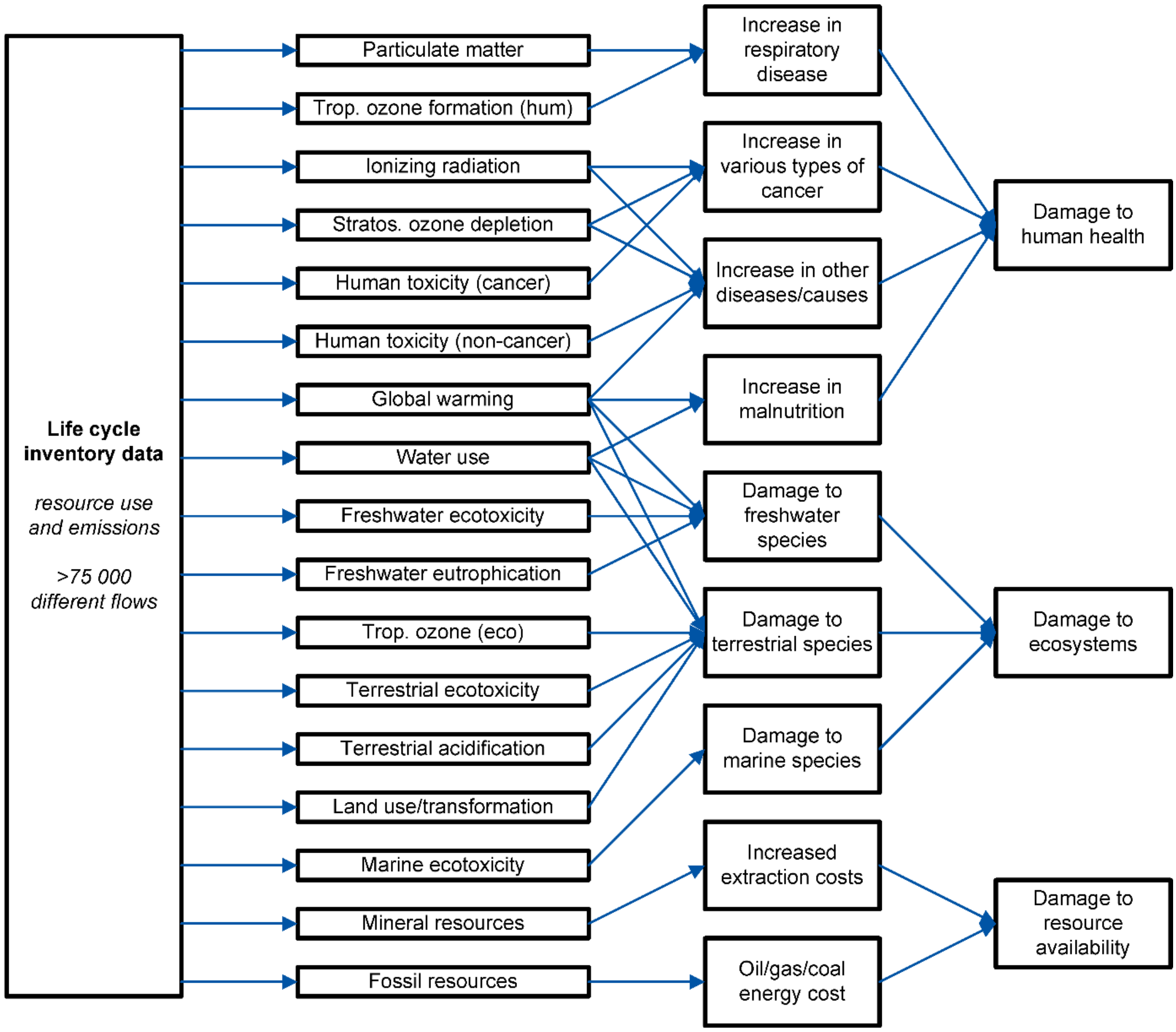

Figure 4: Overview of the ReCiPe method, based on [4]

Economic impact

The economic cost is expressed in euro (2018). As the data used for the economic evaluations are up-to-date, no historic correction is required.

2 Inventory analysis

2.1 Environmental data

In this chapter the needed inputs and outputs are described for the developed OptiNanoPro coating for OPV cells. Where possible data were delivered by OPVIUS and BIOINICIA. Other data needed were taken from the Ecoinvent 3 database.

For the coating of the OPV cells, a PET layer was electrosprayed with the following two solutions [5]:

- 7.5% polylactic acid (PLA) + 69.3% chloroform + 23.2% acetone.
- 1.5% SiO_2 + 98.425% ethanol + 0.075% polyvinylpyrrolidone (PVP).

The PET layer has a thickness of 50 µm and a width of 8 cm [6, 7]. For the electrospraying process the speed of the layer was 1.5 mm/s [5]. In a first testing phase the flow of the solutions was 20 and 15 mL/h, respectively [5]. In a second phase, the flow rates of the two solutions varied between 20 and 25 mL/h for the PLA solution and between 20 and 35 mL/h for the SiO_2 solution [8]. For this report we used a flow rate of 25 mL/h and 30 mL/h, respectively. With the density of the different compounds the mass per m² was calculated.

For PVP there was no dataset available in the Ecoinvent database. Therefore the impact was based on the impact of the reagents needed to produce PVP. In a first step butyrolactone reacts with ammonia to form 2-pyrrolidone and water [9]. In a second step, 2-pyrrolidone reacts with acetylene to form N-vinylpyrrolidone [10]. This compound is polymerised in a last step [11]. The mass of the reagents was determined using stoichiometric calculations.

The coating is put on the OPV cell with a non-optimised sheet-to-sheet process in the current research phase. In a later stage – when more progress is made with the coating – the R2R-lamination process would be used. For the sheet-to-sheet process the electricity needed is between 10 and 40 Wh/m² [7]. For the R2R-lamination process, however, no extra electricity cost would be needed because this process is performed anyway, even without the extra coating [7]. Therefore it was chosen to add no extra electricity usage.

For the waste treatment the average European treatment for PET was chosen. This dataset contains the following treatments: incineration (54.1%) and landfilling (45.9%).

In Table 1 an overview is given of all needed materials and processes as well as the background datasets used to model them.

Table 1: Data inverntory for the OptiNanoPro coating for OPV cells

Inputs	Amount	Unit
Nanocoating production		
PET *Polyethylene terephthalate, granulate, amorphous {GLO}| market for | APOS, U*	69.00	g
SiO_2 *Silica sand {GLO}| market for | APOS, U*	2.24	g
Ethanol *Ethanol, without water, in 95% solution state, from fermentation {RER}| ethanol production from rye | APOS, U*	53.95	g
PVP *components:* *Butyrolactone {GLO}| market for | APOS, U* *Ammonia, liquid {RER}| market for | APOS, U* *Acetylene {GLO}| market for | APOS, U*	0.063	g
PLA *Polylactide, granulate {GLO}| market for | APOS, U*	5.64	g
Chloroform *Trichloromethane {GLO}| market for | APOS, U*	59.72	g
Acetone *Acetone, liquid {GLO}| market for | APOS, U*	10.53	g
End-of-life scenario		
Treatment of waste coating *Waste polyethylene terephtalate {Europe without Switzerland}| market for waste polyethylene terephtalate | APOS, U*	76.94	g

Data about the performance of OPV cells whether or not cleaned are very limited. One test was performed suggesting the effect of cleaning the surface of the OPV cells increases the harvest with minimum 10% [5]. However, a larger scale test of Google for solar panels suggests tilted solar cells don't need cleaning [12]. Because there weren't sufficient data, cleaning the OPV cells was not taken into account as a separate process.

Also the data for the performance of the OPV cells in terms of produced electricity were limited and varied a lot. Coating the OPV cells reduced the light absorption by 5% [5]. The first outdoor testing resulted in a 8% lower electricity production on average for the OPV cells coated with the OptiNanoPro coating [13]. In a second test with slightly adjusted flow rates some coated OPV cells produced less electricity, while others produced 5-8% more electricity [13]. Also the variation in the electricity production between the OPV cells has to be taken into account. This is estimated to be around +/-5% [14]. The coating seems to increase the performance of the OPV cells in some cases and can be promising. This needs however further research because the uncertainty is very high due to differences in performance of the individual OPV cells and the varying results of the OPV cells in terms of electricity production. Because of the high uncertainty concerning the efficiency of the OPV cells coated with the OptiNanoPro coating, it was chosen to calculate the results for a range from -10% up to +10% efficiency compared with uncoated OPV cells. Also the break-even point between coated and uncoated cells is determined.

The yield of the OPV cells is in standard conditions 50 Wp/m² [7]. For the conversion to kWh a conversion factor of 0.85 is used [15]. Keep in mind that this factor depends on the place the OPV cells will be placed. The results can be different for a different region. The lifetime of the OPV cells is estimated to be 20 years, with an efficiency loss of 1% every year [7]. With these numbers the total electricity production per m² during the lifetime of the OPV cell can be calculated: 765 kWh. For the coated OPV cells a range from +/- 10% in electricity production is taken into account. This means the environmental impact of the coated OPV is calculated for an electricity production between 688.5 and 841.5 kWh over their lifetime.

When less than 765 kWh is produced, the difference has to be compensated in order to make a fair comparison with the uncoated OPV cells. When an extra amount of electricity is produced, the surplus should be compensated for the uncoated OPV cells. For this study it was in this case chosen to subtract the impact of the excess amount from the impact of coated OPV cells in order to maintain the same value for the reference scenario (uncoated OPV cells).

To calculate the environmental impact of the different yields, the impact of 1 kWh for the average European electricity production (*Electricity, low voltage {Europe without Switzerland}| market group for | APOS, U*) was taken into account in order to balance the reduced or increased electricity production yield. This impact can be found in Table 2.

Table 2: Impact of 1 kWh average electricity production in Europe

Method	amount	unit
IPCC 2013 GWP 100a	0.48	kg CO_2 eq.
ReCiPe 2016 – human health	1.14E-6	DALY
ReCiPe 2016 – ecosystems	2.48E-9	species.yr
ReCiPe 2016 – resources	0.018	USD2013

2.2 Economic data

The cost of the coating is expressed in euro, for the year 2018. The production costs for an industrial scale was estimated by BIOINICIA and are around 19.55 euro per m². Note that the current pilot scale production costs are around 520.11 euro per m² [13].

Because the R2R-lamination process for laminating the OPV cells is performed anyway, no extra costs have to be made in case of the OptiNanoPro coating [7].

The cost of the end-of-life treatment was difficult to determine because the numbers are very different depending on the source. For example a European study gives an example of incineration costs around 70-75 euro/tonne and a landfill cost between 30-100 euro/tonne [16]. American data for high income countries reports costs of 85-200 dollar/tonne for collection, 40-100 dollar/tonne for landfill, and 70-200 dollar/tonne for incineration [17]. A Dutch study about the incineration of plastic household waste mentions 6 euro/tonne for collection and 60 euro/tonne for incineration [18]. Another European study about waste treatment of plastics estimated a cost of 140 euro/tonne for landfilling PET. For the incineration of PE, PET and PVC the cost was 196, 98 and 380 euro/tonne, respectively [19]. For this study the cost of incineration and landfilling the PET-based coating was both estimated at 100 euro/tonne.

The costs concerning the OptiNanoPro coating can be found in Table 3.

Table 3: Costs related to the OptiNanoPro coating of OPV cells

Inputs	Cost	Currency
Production of OptiNanoPro coating	19.55	euro
Waste treatment of OptiNanoPro coating	0.01	euro

The uncertainty about the performance of the coated OPV cells was handled in the same way as with the environmental impact. A range with varying efficiencies was used and the economic break-even point was determined. For the calculation of the cost of the difference in electricity production, the European average consumer cost of the second half of 2017 was used, namely 0.20 euro/kWh [20]. To convert to costs of 2018 an inflation of 2.14% was taken into account [21]. However, when taken the inflation into account the cost remained 0.20 euro/kWh for the average European electricity production.

3 Impact assessment results

3.1 Environmental results

The carbon footprint and the impact on the ReCiPe endpoint categories were calculated using SimaPro. The results of three different setups are listed in Table 4. Note that for the calculations the impact of the OPV cell itself is not taken into account. The impact is thus only caused by the production of the coating and the difference in electricity production. The results for -10% corresponds to the impact of the coating when the electricity production is 10% lower compared to uncoated OPV cells. In the middle are the results for an equal amount of electricity production. To the right the impact is given when coated OPV cells would produce 10% more electricity compared to the uncoated version. These numbers are negative because the impact of the extra amount of electricity produced is subtracted from the impact of the production to make a comparison possible with the uncoated OPV cells.

Table 4: Results of the impact assessment for OPV cells with 5% less electricity production because of the coating

Method	Amount			Unit
	-10%	0%	+10%	
IPCC 2013 GWP 100a	38.01	1.63	-34.76	kg CO_2 eq.
ReCiPe 2016 – human health	9.06E-5	3.07E-06	-8.44E-5	DALY
ReCiPe 2016 – ecosystems	1.99E-7	9.54E-9	-1.80E-7	species.yr
ReCiPe 2016 – resources	1.44	0.07	-1.31	USD2013

The environmental impact in function of improving efficiency of the OPV cells is shown in Figure 5. The x-axis of this figure represents the percentage difference in electricity production of a coated OPV cell compared to an uncoated OPV cell. The y-axis of this figure represents the relative environmental impact. These are the results of the coated OPV cells compared to the results of the coated OPV cells when the production would be equal to that of the uncoated OPV cells (the scenario where the difference is 0%). This means that the impact of the production and waste treatment of the coating was set to 1 for the results of the carbon footprint and the ReCiPe endpoint categories.

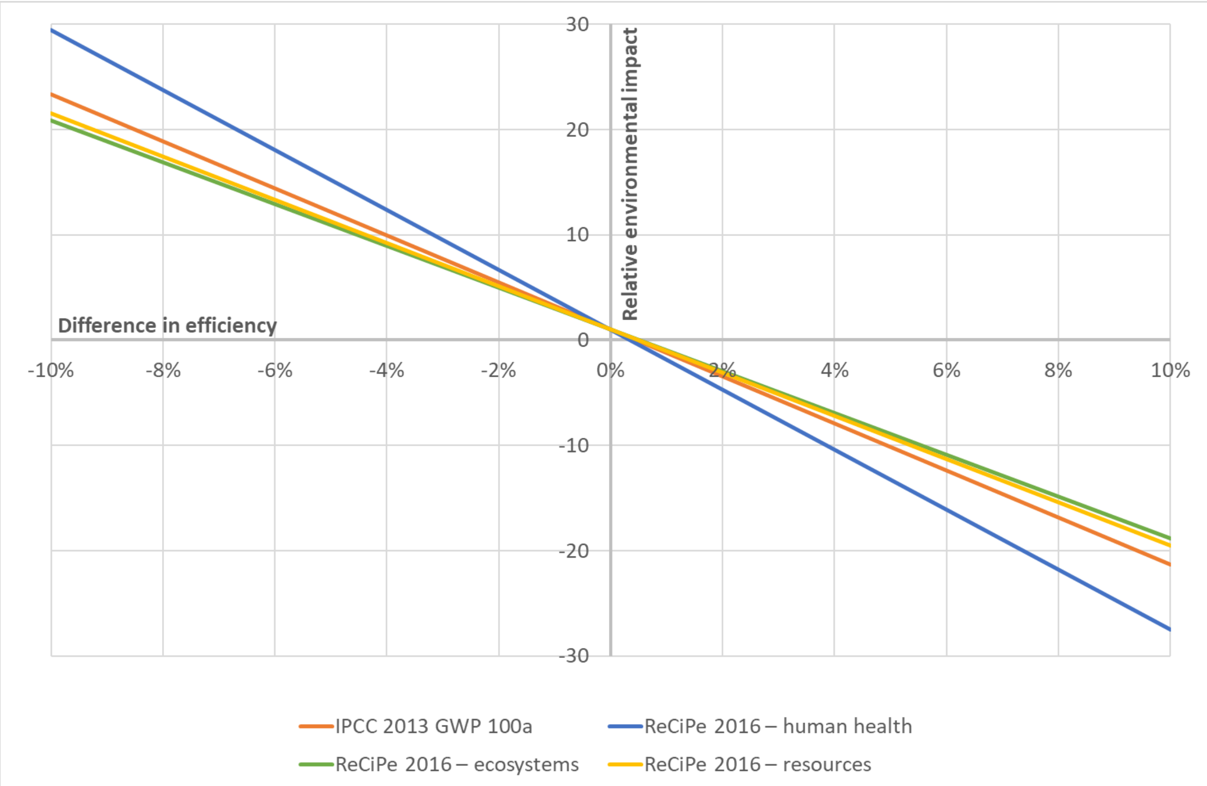

Figure 5: Relative environmental impact in terms of changing efficiency of the electricity production of the coated OPV cells compared to uncoated OPV cells

3.2 Economic results

The economic results per m² of coating for the range from -10% electricity production up to +10% electricity production can be found in Table 5. These numbers represent the cost difference between the coated OPV cells and the uncoated OPV cells. When equal amount of electricity is produced, the cost difference equals the cost of production and waste treatment of the OptiNanoPro coating.

Table 5: Cost per m² of coated OPV cells compared to uncoated OPV cells

Scenario	Cost	Currency
10% less electricity production	34.86	euro
Equal amount of electricity production	19.56	euro
10% more electricity production	4.26	euro

The evolution of the total costs in function of better performing efficiency is shown in Figure 6. Because the break-even point is not reached when the coated OPV cells produce 10% more electricity, the range is extended to +15%.

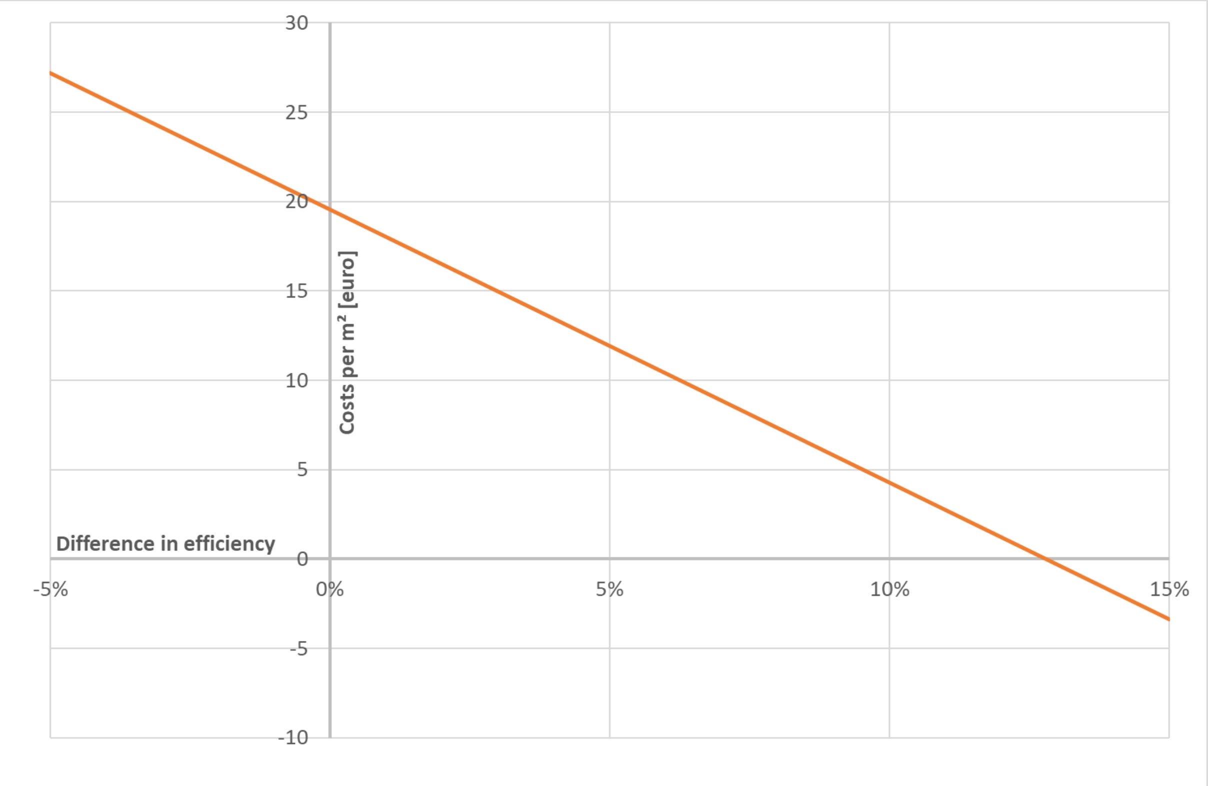

Figure 6: Costs in terms of changing efficiency of the electricity production of the coated OPV cells compared to uncoated OPV cells

3.3 Uncertainty

The uncertainty of the results was measured for all methods taken into account, using Monte Carlo simulations with 1 000 runs and a confidence interval of 95%. The results of the uncertainty assessment are visualised in Figure 7. The uncertainty is quite high for the results of two impact categories of the ReCiPe 2016 endpoint method, namely for the damage to human health and the damage to ecosystems. These results should be used and interpreted with caution as reality can differ from the calculated values. The uncertainty of the other results is low.

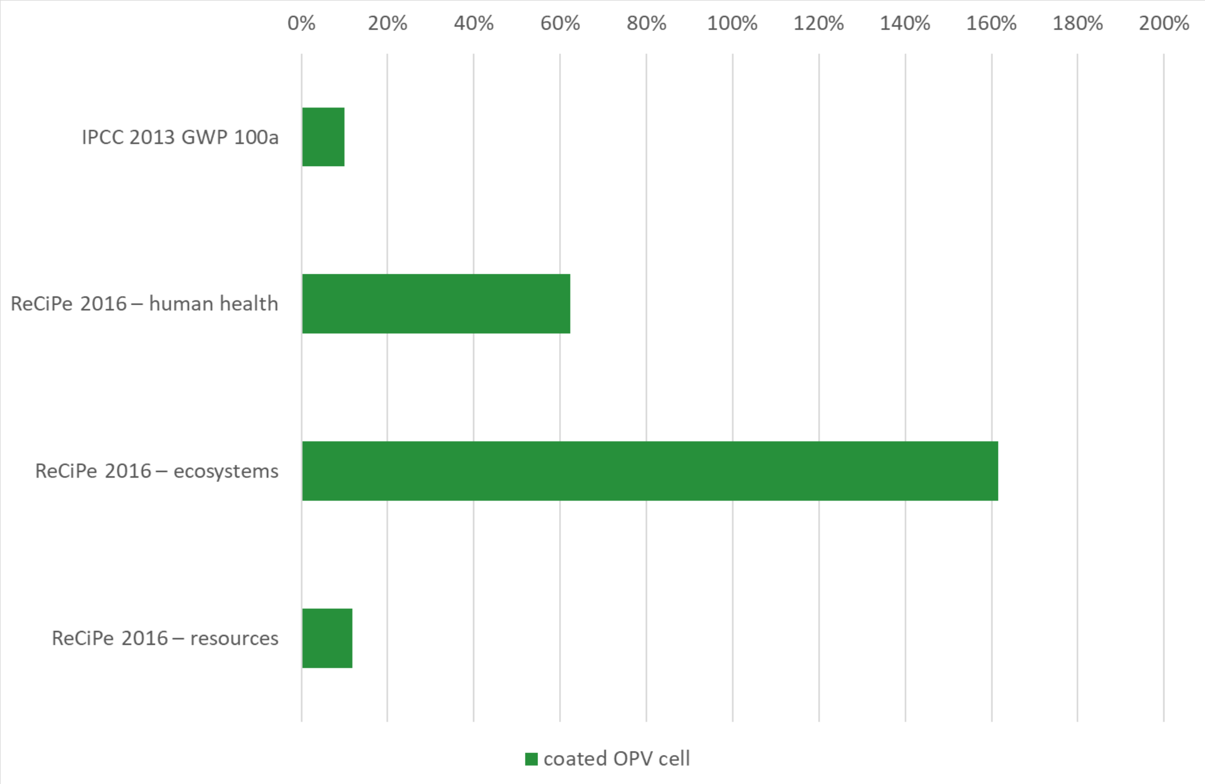

Figure 7: Results of the uncertainty assessment

4 Interpretation and conclusions

In this chapter the results are interpreted and the hotspots of the OptiNanoPro product are discussed. These hotspots represent the most important contributors to the environmental and economic impact. When trying to reduce the impact on the environment the focus should be on these hotspots. The economic hotspots can provide important insights for further improvements towards economically competitive products.

4.1 Environmental impact

4.1.1 Hotspots

The total impact and the hotspots of the OptiNanoPro coating depend of course on the performance of the coated OPV cells. In order to get a clear understanding of the hotspots, two scenarios have been selected. In the first scenario it is assumed the coated OPV cells produce 5% less electricity compared to the uncoated OPV cells. In this way the environmental impact of the extra electricity needed as a compensation can be compared to the impact of the production. In a second scenario it is assumed that coated and uncoated OPV cells produce equal amounts of electricity. This allows to focus on the hotspots of the production and waste treatment of the coating.

The hotspots of the first scenario (5% less electricity production) are presented in Figure 8. The compensation of 38.25 kWh electricity production contributes for around 92% to the total environmental impact in all categories. It can be concluded that for most ranges of efficiency the compensation of electricity will be the dominant factor concerning the environmental impact. The cause of the impact for the average electricity production in Europe will be discussed for each impact category taken into account.

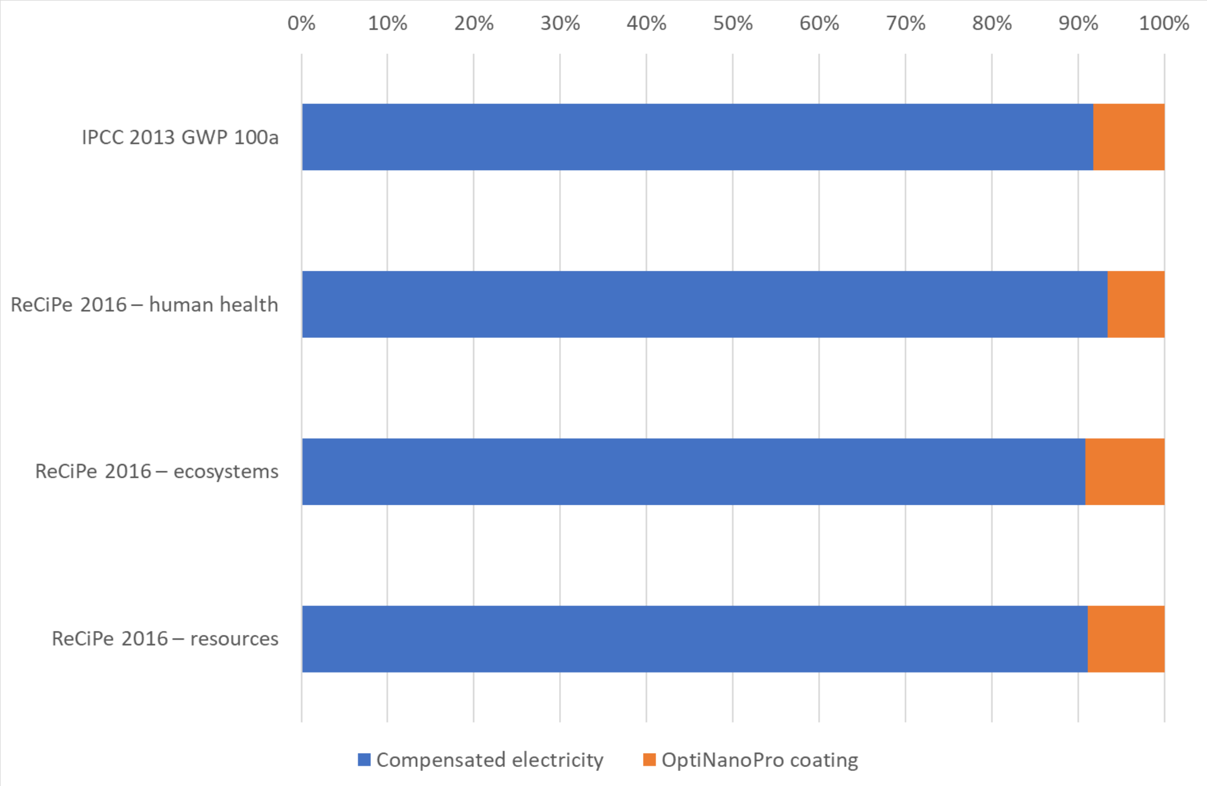

Figure 8: Hotspots of the environmental footprint when coated OPV cells produce 5% less electricity

Climate change

The majority of the impact caused by the electricity production is because of fossil carbon dioxide emissions. These originate mostly from electricity production out of lignite and hard coal.

Damage to human health

In this category the impact is caused by emissions of fossil carbon dioxide, sulfur dioxide, and fine particulates into the air. These emissions are on the one hand caused by the production of electricity with lignite and hard coal. On the other hand also spoils from mining these resources cause these emissions.

Damage to ecosystems

The impact is mainly caused by fossil carbon dioxide and sulfur dioxide emissions to air. The reasons are the same is with the damage to human health: emissions caused by electricity production and processes related to mining.

Resource depletion

The impact is for more than half caused by natural gas use. Also hard coal and uranium use are important. Practically all of the impact is related to the preparation of these resources to produce electricity.

The second scenario is when only the production and waste treatment of the OptiNanoPro coating is taken into consideration. The hotspots of this scenario are visualised in Figure 9. The most important causes of the impact will be discussed for each impact category taken into account.

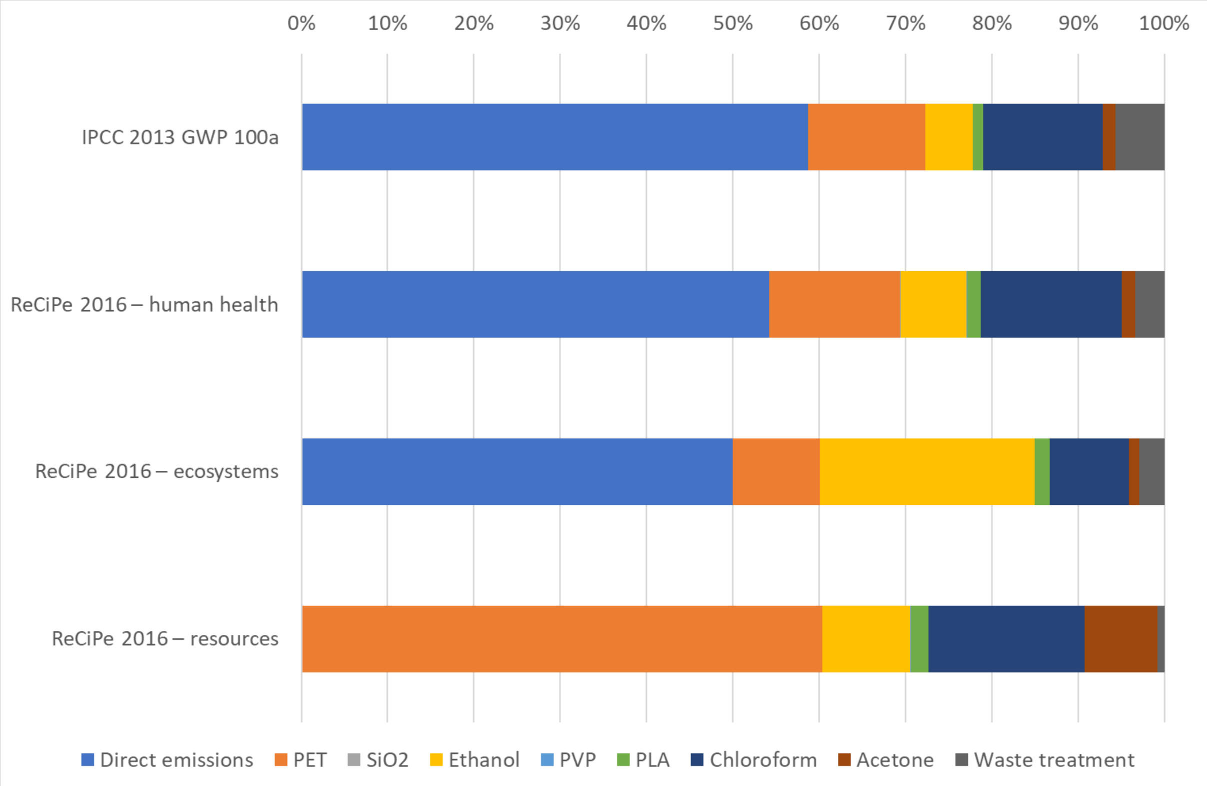

Figure 9: Hotspots of the environmental footprint of the production and waste treatment of the OptiNanoPro coating

Climate change

The majority of the impact is caused by direct emissions caused by the evaporation of ethanol, chloroform, and acetone during electrospraying. Also the use of chloroform and PET contribute for more than 10% to the total impact. When focussing on the reasons behind this impact, it can be concluded that more than half of the impact in this category is caused by chloroform emissions to the air caused by the evaporation during the electrospraying process. Also fossil carbon dioxide emissions are important, mostly originating from the PET and chloroform production.

Damage to human health

Also in this case the direct emissions, and the use of PET and chloroform are the most important. The impact of these processes is caused by chloroform emissions because of the evaporation during electrospraying and fossil carbon dioxide emissions, mainly from processes linked with the PET and chloroform production.

Damage to ecosystems

Half of the impact is caused by the direct emissions mentioned before. Around a quarter is because of the use of ethanol. In this case the most important emissions are from chloroform, ethanol, and fossil carbon dioxide. Chloroform and ethanol emissions originate from evaporation during electrospraying. Carbon dioxide emissions are linked with the production of PET and chloroform. The impact because of the use of ethanol is mainly because of the land used for rye grain production.

Resource depletion

In this impact category the use of PET is most important. Also the use of chloroform and ethanol contribute for at least 10% to the impact. The most important compounds in this case are natural gas and crude oil. The most important processes linked with these compounds are the xylene and ethylene production for making PET. Other processes are the production of natural gas and petroleum used for the production of PET and chloroform.

4.1.2 Changing efficiency

Based on the calculations linked with Figure 5, the environmental break-even point can be determined. This break-even point is reached when the OPV cells coated with the OptiNanoPro coating perform 0.35% to 0.50% better compared to the uncoated OPV cells, depending on the impact category. It can be concluded that to perform better for the environment, the efficiency of the coated OPV cells needs to be increased with more than 0.5%.

4.2 Economic impact

The economic hotspots of two scenarios are calculated: for 5% less and 5% more electricity production. These two scenarios are showed in Figure 10.

The cost of the waste treatment is negligible. When producing 5% less electricity, the production of the coating accounts for around 70% of the cost. When producing 5% more electricity with coated OPV cells compared to uncoated OPV cells, around 40% of the production cost is compensated by the surplus of electricity produced.

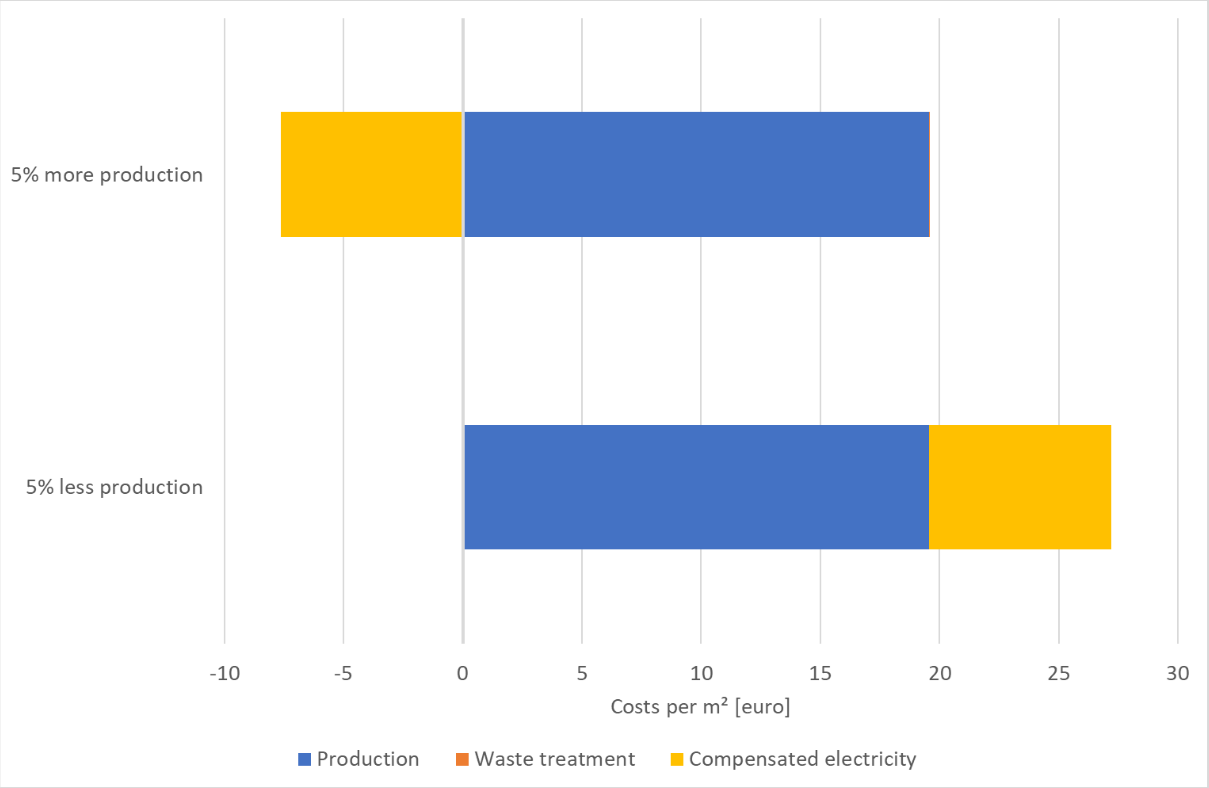

Figure 10: Economic hotspots of the coated OPV cells with 5% more (top) and 5% less (bottom) electricity production

The break-even point for the economic impact between the OPV cells with the OptiNanoPro coating and the uncoated OPV cells can be viewed in Figure 6. The efficiency of the coated OPV cells needs to be a lot higher to reach the break-even point for the economic impact compared to the environmental impact. From an economic point of view the coated OPV cells are only interesting if the efficiency is at least 12.8% higher compared to the uncoated OPV cells.

4.3 Conclusions

First of all it has to be remarked that data about the coated OPV cells are very limited concerning the effect of cleaning and the efficiency in terms of electricity production. Also data about performance and lifetime of the OPV cells is limited. Secondly, the results of the impact in the categories damage to human health and ecosystems – both ReCiPe 2016 endpoint – are quite uncertain. These results should be interpreted with caution.

The environmental footprint of the OPV cells coated with the OptiNanoPro coating is better compared to the uncoated OPV cells if the production of the coated OPV cells is at least 0.5% higher. Concerning the production of the coating, the direct emissions of mainly chloroform during electrospraying is very important. For resource depletion the most important factors are the natural gas and crude oil linked with PET production.

The total cost of the coating is 19.56 euro per m² for production on industrial scale and waste treatment. The coated OPV cells are economically more viable if the electricity production is at least 12.8% higher compared to the uncoated OPV cells.

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