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High-performance low-cost modules with excellent environmental profiles for a competitive EU PV manufacturing industry

HighLite- Deliverable report

D8.2- Intermediate Environmental Evaluation

Disclaimer/ Acknowledgment

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About HighLite

The HighLite project aims to substantially improve the competitiveness of the EU PV manufacturing industry by developing knowledge-based manufacturing solutions for high-performance low-cost modules with excellent environmental profiles (low CO_2 footprint, enhanced durability, improved recyclability). In HighLite, a unique consortium of experienced industrial actors and leading institutes will work collectively to develop, optimize, and bring to high technology readiness levels (TRL 6-7) innovative solutions at both cell and module levels.

HighLite consortium members

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Dissemination level[2]

PU	**Public**	X
CO	**Confidential, only for members of the consortium (including the Commission Services)**	

[1] **Deliverable Type**
Please indicate the type of the deliverable using one of the following codes:
R Document, report
DEM Demonstrator, pilot, prototype
DEC Websites, patent fillings, videos, etc.
OTHER
ETHICS Ethics requirement
ORDP Open Research Data Pilot
DATA data sets, microdata, etc.

[2] **Dissemination level**
Please indicate the dissemination level using one of the following codes:
PU Public
CO Confidential, only for members of the consortium (including the Commission Services)
EU-RES Classified Information: RESTREINT UE (Commission Decision 2005/444/EC)
EU-CON Classified Information: CONFIDENTIEL UE (Commission Decision 2005/444/EC)
EU-SEC Classified Information: SECRET UE (Commission Decision 2005/444/EC)

Publishable summary

The D8.2 deliverable report (Intermediate environmental report) provides a detailed view on how the carbon footprint goal of the HighLite project can be achieved (250 kg CO2-eq./kWp). This goal shows the high environmental ambition level of the project. It means a reduction of the carbon footprint of state-of-the-art PV modules (1120 kg CO2-eq./kWp) by almost 80%. The report shows what is needed for this goal to be achieved.

To this end, a reference PV module is defined representing state-of-the-art PV technology. The life-cycle inventory data required to calculate a breakdown of the carbon footprint of this reference were assembled using, a.o., data published by the IEA PVPS Task 12 group, an international experts group in the area of PV sustainability. The calculations were carried out using the commercial LCA software Simapro in conjunction with the Ecoinvent database. A (module level) carbon footprint of 1120 kg CO2-eq./kWp was found.

Based on this reference value, a systematic analysis of carbon footprint reduction potentials was carried out. The focus of this analysis was on reduction potentials arising from specific goals of the HighLite project, such as 22% PV module efficiency (WP5) as well as the implementation of thin wafers down to 100 µm (WP4) and frameless glass/glass module configuration (WP5). With these innovations significant carbon footprint reductions on the order of ~ 25% can be expected. However, these innovations alone will not suffice to reach the carbon footprint goal of the HighLite project.

Therefore, other additional potentials to reduce the carbon footprint are also analysed and documented in the report. This analysis reveals that the use of “green electricity” with very low inherent carbon footprint (such as hydropower) is pivotal to achieve further large reductions of the carbon footprint. When implementing this type of “green electricity” throughout the entire PV value chain, further carbon footprint reduction by as much as ~ 60% can be achieved.

The conclusion of this analysis is that the carbon footprint goal of the project is achievable, but requires large efforts not only within the direct project scope, but also beyond.

Contents

List of acronyms, abbreviations and definitions

Abbreviation	Definitions
BAPV	Building Added Photovoltaics
EoL	End-of-Life
IEA PVPS T12	International Energy Agency Photovoltaic Power Systems, Task 12 (PV Sustainability)
LCA	Life-Cycle Assessment
LCI	Life-Cycle Inventory

1. Introduction

The objective of WP8 (M13-M36) is to analyse the project results in terms of economic and environmental impacts by carrying out cost and environmental footprint calculations for the technologies developed in "HighLite " and translating the results into meaningful metrics. Results to be generated in WP8 are, the quantification of economic and environmental characteristics, such as:

- Cost of ownership, CoO, at module level (in €ct/Wp)
- Levelized cost of electricity, LCOE, at system level (in €ct/kWh)
- Carbon footprint (in kg CO2-eq./kWp and g CO2-eq./kWh)
- Detailed view how to achieve environmental goal of the project (< 250 kg CO2-eq./kWp)

D8.2 (Report on intermediate environmental evaluation) is a deliverable within task T8.2 (Environmental Analysis). This task focuses on the environmental aspects of WP8 and applies life-cycle assessment methods, LCA, as an analytical tool. The main purpose of D8.2 is to address the last point of the bullet list above, i.e., to provide a detailed view on how the ambitious carbon footprint goal of the project can be achieved.

Table 1: Overview of deliverable D8.2.

Deliverable Number	Short deliverable name	Lead beneficiary	Type	Dissemination level	Due date
D8.2	Intermediate Environmental Evaluation	TNO	R	PU	M18

2. Work performed for deliverable

2.1. Approach

In order to obtain a detailed view on how the ambitious carbon footprint goal of HighLite (250 kg CO2-eq./kWp) can be achieved, a reference technology needed to be defined first as a basis to calculate a reference carbon footprint. Significant parts of the life-cycle inventory data for the reference technology were extracted from the most recent publication[3] of IEA PVPS Task 12, an international experts group in the area of PV sustainability in which TNO has a seat. The reference technology represents state-of-the-art PV module technology. Characteristic parameters that are relevant for the LCA calculations are given here below:

- Location of manufacturing (all components): China
- Electricity for all manufacturing processes: Chinese mix (1180 g CO2-eq./kWh)
- Silicon (solar grade): Modified Siemens process (electricity consumption: 49 kWh/kg)
- Ingot technology: Cz (electricity consumption: 32 kWh/kg)
- Wafering technology: diamond wire-sawing (kerf loss: 65 µm)
- Wafer thickness: 170 µm
- PV module configuration: monofacial, glass/backsheet + aluminium frame
- PV module efficiency: 19,0%

With the reference carbon footprint as a basis, reduction potentials were analysed by LCA calculations (using the commercial software Simapro in conjunction with the Ecoinvent database). A difference was made between reduction potentials resulting directly from the goals/innovations of the HighLite project and other reduction potentials.

The carbon footprint reduction potentials of the HighLite goals analysed in this report are:

- PV module efficiency (BAPV): 22%
- Wafer thickness: 100 µm
- PV module configuration: frameless glass/glass

Other carbon footprint reduction potentials analysed in this report are:

- the use of "green electricity" (rather than the carbon intense Chinese electricity mix) throughout the entire supply chain, i.e., for the production of solar grade silicon, ingots, wafers, cells and modules.

[3] Rolf Frischknecht e.a., *Life Cycle Inventories and Life Cycle Assessments of Photovoltaic Systems*, Report IEA-PVPS T12-19:2020, December 2020. Life Cycle Inventories and Life Cycle Assessments of Photovoltaic Systems (iea-pvps.org)

2.2. Results obtained

Figure 1 shows the breakdown of the carbon footprint of the reference PV module into its various components, i.e., “Si feedstock (solar grade)”, “Ingot/wafers production”, “Solar cell processing”, “Solar glass”, “Encapsulant”, “Backsheet”, “Electricity for lamination”, “Rest of module manufacturing (e.g. j-box, Cu tabs)”.

It is clear from Figure 1 that the dominant module component by far regarding the carbon footprint are the silicon wafers which embody the carbon footprint associated with “Si feedstock (solar grade)”, 35%, and “Ingot/wafer production”, 22%. So, the wafers alone represent ~ 57% (!) of the entire carbon footprint of the reference PV module.

Next to the silicon wafers, there are 5 further components in this breakdown with significant contributions to the carbon footprint (on the order of 5-10% each). These are:

- “Aluminium frame” (8%),
- “Solar glass” (5%),
- “Solar cell processing” (11%),
- “Electricity for lamination” (7%)
- “Rest of module manufacturing (8%).

The absolute value of the carbon footprint of the reference PV module is ~ 1120 kg CO2-eq./kWp.

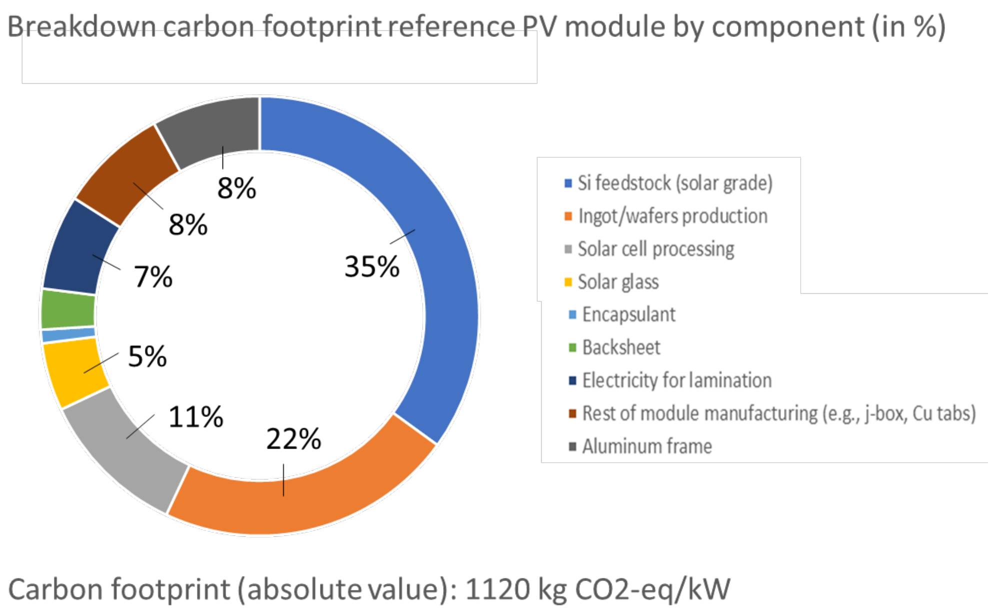

Figure 1: Breakdown of carbon footprint of reference PV module.

With the results obtained from the LCA calculations of the reference PV module, it is obvious that the carbon footprint goal of the HighLite project (250 kg-CO2-eq./kWp) is very ambitious. It represents a decrease of almost 80% compared to the reference value (1120 kg CO2-eq./kWp). This ambitious goal can only be achieved when very major carbon footprint reductions are realized throughout the entire supply chain. The HighLite goals/innovations alone will not suffice (as will be shown below).

In the following we discuss approximate carbon footprint reduction potentials of the HighLite goals one by one as well as other potentials (arising from the use of "green electricity" throughout the supply chain).

HighLite goal of 22% PV module efficiency, BAPV:

Efficiency improvement is a very powerful way to reduce the carbon footprint. It acts on all components of the carbon footprint at the same way, because the efficiency improvement simply results in a **larger denominator** of the overall carbon footprint unit (g CO2-eq./**kWp**). A reasonable approximation is to equate the carbon footprint reduction potential by the efficiency ratio. This is because any possible carbon footprint increase on the level of the solar cell processing and/or module manufacturing – needed to achieve the higher module efficiency - can safely be assumed to be small. So, this results in a carbon footprint reduction potential of approximately 1-19/22 = ~ 15%

- **The (module level) carbon footprint reduction potential is ~ 15%.**

HighLite goal of using wafers as thin as 100 µm:

Estimating the carbon footprint reduction potential for the application of thinner wafers is more complex. However, the correlation between wafer thickness and carbon footprint was investigated in the EU project CHEETAH. For various reasons, such as a constant kerf loss (independent of final wafer thickness) as well as lower yields for the more fragile thin wafers, the improvement potential of thinner wafers is significantly lower than the ratio of the wafer thicknesses. For a wafer thickness of 100 µm, a carbon footprint reduction potential of ~ 20% (relative to the 170 µm reference wafers) is assumed here. On the module level, this translates into approximately 20%·57% = 11%.

- **The (module level) carbon footprint reduction potential is ~ 11%.**

HighLite goal of frameless glass/glass modules:

As shown in Figure 1, the aluminium frame represents ~ 8% of the carbon footprint of the PV module. So, by removing the frame, the carbon footprint decreases correspondingly. However, the frameless glass/glass configuration is not only characterized by the absence of the aluminium frame (and backsheet), but at the same time by the presence of an additional (second) glass pane. In this way, the change from a glass/backsheet configuration with frame to a frameless glass/glass one is somewhat of a zero sum game. At least, this is the case if the thickness and nature of the two glass panes in the glass/glass configuration is the same as that of the reference PV module. For thinner glass panes and/or lesser glass quality for the backside pane (i.e., not low-iron solar quality), small carbon footprint reductions can nevertheless be achieved.

- **The (module level) carbon footprint reduction potential is estimated to be ~ 2%.**

Other carbon footprint reduction potentials:

A pivotal background factor for all components of the carbon footprint shown in Figure 1 is the electricity requirements for the various manufacturing processes throughout the PV supply chain. These dominate (by large and by far) the carbon footprints of essentially all components in the breakdown. In the reference PV module, the requirements are assumed to be met by the Chinese electricity mix. This electricity mix is currently still characterized by a very large fraction of coal-fired power generation. Consequently, this electricity mix is associated with a large carbon footprint. Electricity mixes of most countries in Europe are less carbon intensive, but those of e.g., France and Norway stand out by far (due to the high share of nuclear power in the French and hydropower in the Norwegian electricity mix).

The carbon footprints of the electricity mixes of the three countries discussed above are:

- China: 1180 g CO2-eq./kWh
- France: 95 g CO2-eq./kWh
- Norway: 36 g CO2-eq./kWh

We note that the carbon footprint of the Norwegian electricity mix amounts to only ~ 3% of the value of the Chinese electricity mix. So, by implementing this type of truly "green electricity" inputs into the silicon supply chain, the carbon footprint of the PV modules can be further dramatically reduced. This enormous carbon footprint reduction potential is also reflected by recent press releases of Norwegian silicon producers[4]. Within the scope of this report, we estimate on the basis of the Norwegian electricity mix following further potentials: ~ 50% (module level) reduction potential for the use of "green electricity" throughout the supply chain up to the silicon wafers and ~ 10% (module level) reduction potential for the use of green electricity in the cell and module production

- **The (module level) carbon footprint reduction potential is estimated to be ~ 60%.**

The various carbon footprint reduction potentials discussed above are summarized in the waterfall chart of Figure 2 below. As can be seen in this figure the sum of these potentials leads to a reduction of the carbon footprint down to 276 kg CO2-eq./kWp, which is close to the project target. A few extra achievements, e.g. the elimination of the aluminium frame or innovations resulting in the allocation of life-cycle credits for (silicon) recycling, will allow to reach the carbon footprint goal of the project.

[4] E.g.
- REC Solar Norway AS has received certification for Environmental Product Declarations (EPDs) for silicon and multicrystalline blocks for use in solar cells | REC Group,
- 2021 02 01 NorSun Wafers first in the industry to receive EPD (norsuncorp.no)

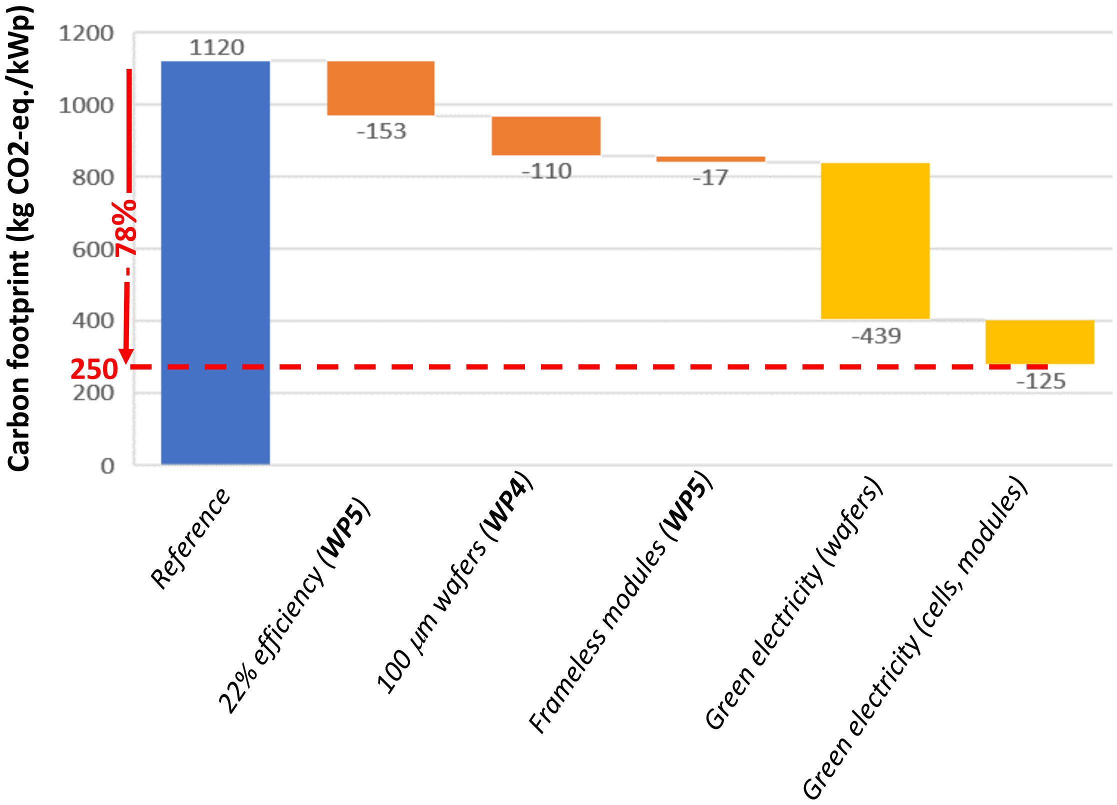

Figure 2: Waterfall chart showing carbon footprint potentials associated with the HighLite project goals (orange) as well as other potentials (yellow).

3. Risks encountered and expected impacts

3.1. Risks/problems encountered

One of the critical tasks in any environmental evaluation is the gathering of accurate and up-to-date information on the processes involved and their inputs (materials, energy, water use, etc.) and outputs (products, waste, emissions to the environment, etc.). This information is needed for the HighLite innovations as well as for benchmark products.

One of the complications in determining the environmental impact for the HighLite innovations is that they are still under development. Therefore, the inputs and outputs are not yet fully known, even at lab scale. It will be even more challenging to estimate the inputs and outputs of full-scale manufacturing processes. To overcome this one could use a prospective life cycle assessment.

When it comes to environmental evaluations of benchmark products one will have to rely on environmental assessments performed by external parties. They might use a different set of assumptions than are used in the assessment of the products developed within the HighLite project. This would make comparison of the outcome not valid. To overcome this problem one should focus on well-documented LCAs that follow a standard methodology, preferably the European standard Product Environmental Footprint Category Rules (PEFCR) for PV modules[5].

3.2. Expected impacts

The HighLite project aims to develop high-performance low-cost modules with excellent environmental profiles for a competitive EU PV manufacturing industry. One of the targets is to develop a PV module with a GHG emissions during production of less than 250 kg CO2-eq./kWp. This radically improved environmental performance is essential for the EU PV manufacturing industry to be competitive internationally.

This is increasingly important as the EU is in the process of implementing Eco-Design and Energy Labelling measures for PV modules, inverters and systems. New mandatory performance and quality requirements are being considered as well as mandatory information requirements, based on a preparatory study[6] carried out by JRC from 2017 to 2019 [Dodd 2019].

For PV modules the preparatory study recommends mandatory product durability tests, as well as the following information requirements:

- Lifetime module energy yield
- Lifetime performance degradation
- Repairability
- Dismantlability
- Material disclosure
- Life cycle primary energy (GER) and Global Warming Potential (GWP).

[5] PEFCR PV Electricity v1.2 February 2020. PEFCR_PV_electricity_feb2020_2.pdf (europa.eu)
[6] Dodd, Nicholas; Espinosa, Nieves – JRC B5; Preparatory study for solar photovoltaic modules, inverters and systems, (Draft) Task 8 Report: Policy recommendations; December 2019. 20191220 Solar PV Preparatory Study_Task 8_Final version.pdf (europa.eu)

In addition, an Energy Label for solar PV systems installed on residential buildings is proposed, that should specify the system yield-based Energy Efficiency Index (EEI), expressed in units of MWh/(kWp m^2). At the time of publication of this report a market consultation process is on-going. Based on this, the European Commission expects to publish their draft policy measures in the second half of 2021.

4. Conclusions

In this report a systematic analysis was carried out of carbon footprint reduction potentials within the HighLite project.

First of all, the carbon footprint goal of the HighLite project (250 kg-CO2-eq./kWp) was compared with the carbon footprint of a reference PV module. From these calculations it is obvious that **the carbon footprint goal of the HighLite project is very ambitious. It represents a decrease of almost 80% compared to the reference value (1120 kg CO2-eq./kWp).**

Secondly, the carbon footprint reduction potentials were calculated arising from specific project goals, such as 22% PV module efficiency (WP5) as well as the implementation of thin wafers down to 100 mm (WP4) and frameless glass/glass module configuration (WP5). With these innovations significant carbon footprint reductions on the order of ~ 25% can be expected. However, these innovations alone will not suffice to reach the carbon footprint goal of the HighLite project.

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