
Life Cycle Assessment of a Perovskite Silicon Tandem Photo- voltaic Panel

Authors

Livia Ramseier, Philippe Stolz, Rolf Frischknecht

commissioned by

Swiss Federal Office of Energy SFOE

Uster, 3. April 2019

Imprint

Title	Life Cycle Assessment of a Perovskite Silicon Tandem Photovoltaic Panel
Authors	Livia Ramseier, Philippe Stolz, Rolf Frischknecht treeze Ltd., fair life cycle thinking Kanzleistr. 4, CH-8610 Uster www.treeze.ch Phone +41 44 940 61 91, Fax +41 44 940 61 94 info@treeze.ch
Commissioner	Swiss Federal Office of Energy SFOE
Copyright	All content provided in this report is copyrighted, except when noted otherwise. Such information must not be copied or distributed, in whole or in part, without prior written consent of treeze Ltd. or the customer. A provision of this report or of files and information from this report on other websites is not permitted. Any other means of distribution, even in altered forms, require the written consent. Any citation naming treeze Ltd. or the authors of this report shall be provided to the authors before publication for verification.
Liability Statement	Information contained herein have been compiled or arrived from sources believed to be reliable. Nevertheless, the authors or their organizations do not accept liability for any loss or damage arising from the use thereof. Using the given information is strictly your own responsibility.
Version	174_LCA_Perovskite_v1.0.docx, 03/04/2019 18:15:00

Abbreviations and Acronyms

AC	alternating current
CED	cumulative energy demand
CH	Switzerland
CHEOPS	Production technology to achieve low Cost and Highly Efficient photovoltaic Perovskite Solar cells
EF	environmental footprint
EVA	ethylene-vinyl-acetate
GLO	global average
KBOB	Coordination Group for Construction and Property Services (Koordinationskonferenz der Bau- und Liegenschaftsorgane des Bundes)
kWh	kilowatt hour
LCA	life cycle assessment
LCI	life cycle inventory analysis
LCIA	life cycle impact assessment
mPt	milli-points
MJ	mega joule
OXPV	Oxford Photovoltaics Ltd.
p	piece
PEF	product environmental footprint
PEFCR	product environmental footprint category rule
PV	photovoltaic
RER	Europe
tkm	tonne kilometre (unit for transportation services)
UVEK	Federal Department of the Environment, Transport, Energy and Communication

Summary

Perovskite silicon tandem photovoltaic (PV) panels are seen as a new and promising technology with a high efficiency (Sahli et al. 2018). The European research project “Production technology to achieve low Cost and Highly Efficient photovoltaic Perovskite Solar cells” (CHEOPS) aims to further improve the technology and facilitate its commercialisation¹. Within the CHEOPS project, de Wild-Scholten (2017) performed a screening-level life cycle assessment (LCA) of perovskite silicon tandem modules. The goal of this study was to transfer the LCI of perovskite silicon tandem modules published by de Wild-Scholten (2017), which is based on ecoinvent data v3.3, to UVEK life cycle inventory data DQRv2:2018 (KBOB et al. 2018). The functional unit of this study was 1 m² of a perovskite silicon tandem photovoltaic panel.

The environmental impacts of the perovskite silicon tandem photovoltaic panel were quantified with the environmental footprint (EF) impact assessment method (Fazio et al. 2018). The toxicity related impact categories were excluded from the analysis. In addition non-renewable cumulative energy demand and the renewable cumulative energy demand based on Frischknecht et al. (2015b) were quantified. Furthermore, the environmental impacts are compared to those of the production of a single crystalline silicon PV panel.

The total environmental impacts are 64.5 milli-points (mPt)/m² perovskite silicon tandem photovoltaic panel. The impact categories “Resource use, mineral and metals”, “Climate Change”, “Respiratory inorganics”, “Resource use, energy carriers” and “Acidification terrestrial and freshwater” contribute the most to the overall environmental impact. In all these impact categories except “Resource use, mineral and metals” the production of the single crystalline silicon photovoltaic cell in China is the major contributor to the environmental impact. The reason for the high contribution of the single crystalline silicon cell is the high share of hard coal power plants in the Chinese electricity mix and the high electricity demand in the supply of single crystalline silicon ingot. For the impact category “Resource use, mineral and metals” the production of the metallization paste is mainly responsible for the resource depletion of mineral and metals. The comparison between the production of a perovskite silicon tandem photovoltaic panel and a single crystalline silicon photovoltaic panel revealed that the environmental impacts of traditional single crystalline silicon PV panel are between 1 % (respiratory effects) to 5 % (resource use, fossil fuels) lower, except for resource use, mineral and metal the environmental impacts were 61 % lower. Hence, the perovskite silicon tandem PV panel would need to be 1 % to 5 % more efficient than the single silicon PV panel to have a similar environmental impact per kWh produced, disregarding mineral resource use impacts.

¹ <http://www.cheops-project.eu/>, last visited: 21.03.2019

Content

1	INTRODUCTION	1
2	OBJECTIVE AND SCOPE	2
2.1	Objective	2
2.2	Functional unit	2
2.3	Data sources	2
2.4	Impact assessment methods	2
3	LIFE CYCLE INVENTORY	4
4	LIFE CYCLE IMPACT ASSESSMENT	6
4.1	Overview	6
4.2	EF method - Single score	6
4.3	EF method - Midpoints	8
4.4	Cumulative energy demand – non-renewable and renewable	11
4.5	Data quality considerations	13
5	CONCLUSIONS	13
	REFERENCES	14

1 Introduction

The crystalline silicon photovoltaic (PV) technologie is dominating the photovoltaic market today. Continuous research lead to an improvement in efficiencies, which are now approaching the theoretical efficiency limit (Battaglia et al. 2016). Perovskite silicon tandem PV panels are seen as a new and promising technology with a high efficiency (Sahli et al. 2018). The concept of tandem PV panels is to have multiple solar cells with different band gaps to convert more sunlight into electrical energy. In a perovskite silicon tandem PV panel a silicon solar cell is combined with a cell based on organometallic halide compounds with the perovskite crystal structure. In the past years progress was made in improving efficiency at lab scale. However upscaling and stability issues are under discussion (accelopment AG 2016). Itten and Stucki (2017) performed a prospective Life cycle assessment (LCA) comparing perovskite silicon tandem panels with crystalline silicon based solar panels. Their analysis was based on different prospective technology scenarios (incl. efficiency) allowing for a comparison of 1 kWh low voltage alternating current (AC) delivered to the electricity network. Itten and Stucki (2017) concluded that with a lifetime comparable to that of crystalline silicon solar cells, perovskite tandem solar cells cause “similar or lower environmental impacts”.

The European research project “Production technology to achieve low Cost and Highly Efficient photovoltaic Perovskite Solar cells” (CHEOPS) aims to further improve the perovskite technology and facilitate its commercialisation². Within the CHEOPS project, de Wild-Scholten (2017) performed a screening-level life cycle assessment (LCA) of perovskite silicon tandem modules. The life cycle inventory (LCI) was based on primary data provided by Oxford Photovoltaics Ltd. (OXPV) for a factory located in Germany. The analysed perovskite silicon tandem modules are still in development and not yet produced at a commercial scale (de Wild-Scholten 2017).

The goal of this study is to transfer the LCI of perovskite silicon tandem modules published by de Wild-Scholten (2017), which is based onecoinvent data v3.3, to UVEK life cycle inventory data DQRv2:2018 (KBOB et al. 2018). The use of this background database makes the LCI of silicon perovskite tandem PV modules consistent with the LCIs of PV systems developed within IEA PVPS Task 12 (Frischknecht et al. 2015a).

² <http://www.cheops-project.eu/>, last visited: 21.03.2019

2 Objective and scope

2.1 Objective

The objective of this study was to analyse the environmental impacts of a perovskite silicon tandem PV panel based on an existing life cycle inventory published by de Wild-Scholten (2017). The life cycle inventory was linked to UVEK life cycle inventory data DQRv2:2018 (KBOB et al. 2018). The environmental impacts of the perovskite silicon tandem PV panel were analysed based on the Environmental Footprint (EF) impact assessment methods (Fazio et al. 2018). In addition the environmental impacts of the perovskite silicon tandem PV panel were compared to the environmental impacts of a single crystalline silicon PV panel.

2.2 Functional unit

The functional unit of this study is 1 m² of a perovskite silicon tandem photovoltaic panel. As the panel under study is under development there are so far no estimations of panel efficiency and lifetime which would be needed to assess the environmental impacts per kWh PV electricity (de Wild-Scholten 2017).

2.3 Data sources

The life cycle inventory by de Wild-Scholten (2017) was linked to UVEK life cycle inventory data DQRv2:2018 (KBOB et al. 2018), which are based on ecoinvent data v2.2 (ecoinvent Centre 2010). This data source contains extensive updates on energy supply and material production datasets. It ensures methodological continuity with former versions of the ecoinvent database and is used by the Swiss administration. The analyses were performed with SimaPro v8.5.2 (PRé Consultants 2018).

2.4 Impact assessment methods

The environmental impacts of the perovskite silicon tandem PV panel and the single crystalline silicon PV panel were quantified with the environmental footprint (EF) impact assessment method (Fazio et al. 2018). A SimaPro-compatible (“adapted”) version of this method was used, which accounts for additional elementary flows that are frequently used in this software³. Additional adjustments were made in the impact category “water scarcity” in order to quantify water consumption rather than water

³ Personal communication Michiel Oele, Pré Consultants, 06.02.2019.

withdrawal in combination with UVEK life cycle inventory data DQRv2:2018⁴. To this end, the country-specific elementary flows for water emitted to air and for water embodied in product were taken into account using the characterisation factors provided in the EF impact assessment method. The water scarcity impacts of water withdrawal in unspecified regions were assessed following default assumptions. Frischknecht and Büsser Knöpfel (2013) reported that approximately 10 % of process water and 5 % of cooling water are typically evaporated. The global average characterisation factors of the EF impact assessment method were adjusted accordingly to assess the 10 % and 5 % water lost (consumed) and not the water withdrawn.

According to the procedure described in PEFCR guidance (European Commission 2017) the three toxicity related impact categories were excluded from the analysis. The normalization and weighting factors described in European Commission (2017) were applied to quantify the total environmental impacts (single score). Long-term emissions were not included in the impact assessment.

The following five impact categories on midpoint level, which were previously identified as most relevant for PV electricity (TS PEF Pilot PV 2018), are analysed in more detail:

- Climate change (sum fossil, biogenic, land transformation);
- Respiratory inorganics;
- Resource use, energy carriers;
- Resource use, minerals and metals;
- Acidification terrestrial and freshwater.

The non-renewable cumulative energy demand and the renewable cumulative energy demand based on Frischknecht et al. (2015b) are used as additional indicators.

The ILCD midpoint 2011 impact assessment method (European Commission et al. 2012) is used to compare the impact assessment results of this study with the results published by de Wild-Scholten (2017).

⁴ The amounts of water withdrawn from nature and of water evaporated, embodied in product or released to nature or a wastewater treatment plant are usually not balanced in UVEK life cycle inventory data DQRv2:2018. This results in an overestimation of water scarcity impacts according to the EF impact assessment method.

3 Life cycle inventory

De Wild-Scholten (2017) analysed a perovskite silicon tandem PV panel with an area of 1.6 m² comprising 6 x 10 mono-crystalline silicon cells each with a size of 156 mm x 156 mm. The perovskite composition is made out of lead-iodide and methyl-ammonium-iodide. The panel is completed by a double glazing. The module frame is made of aluminium.

The LCI for the production of a perovskite silicon tandem PV panel in Germany published by de Wild-Scholten (2017) was linked to UVEK life cycle inventory data DQRv2:2018 (KBOB et al. 2018). The following adaptations were made compared to the original LCI:

- de Wild-Scholten (2017) used an updated dataset to model the production of monocrystalline silicon solar cells in China, which is not yet publicly available. In this study, the corresponding life cycle inventory based on Frischknecht et al. (2015a) was used (see Table 3-1).
- The solvents 1 (organic, halogen free) and 2 (organic, halogen containing) reported in Table 2 by de Wild-Scholten (2017) were linked to the process “solvent, organic, unspecified at plant” instead of using the generic chemical dataset “chemicals, organic, at plant”.
- The incineration of the cutting loss of the ethylene-vinyl-acetate (EVA) foil (3.1 weight-% according de Wild-Scholten (2017), Table 2) was added to the LCI.
- The loss of cooling water was assumed to be 5 % (Frischknecht & Büsser Knöpfel 2013) and added to the LCI.
- The transport distances were calculated according to the distances provided by OXPV (see Table 2 in de Wild-Scholten (2017)).
- The LCI data for the production of methyl iodide, iodine, ethylene bromide and bromine were newly included in the UVEK life cycle inventory data DQRv2:2018 (KBOB et al. 2018) based on the LCI data provided inecoinvent 3.3 (ecoinvent Centre 2016) for those processes.

In Table 3-1 the adapted LCI for a perovskite silicon tandem PV panel produced in Germany is shown.

Table 3-1: LCI of perovskite silicon tandem modules based on de Wild-Scholten (2017).

Name	Location	Infrastructure Process	Unit	photovoltaic panel, perovskite-Si-tandem, at plant	Uncertainty Type	Standard Deviation 95%	General Comment
product	photovoltaic panel, perovskite-Si-tandem, at plant	DE	1	m2	1		
resource, in water	Water, cooling, unspecified natural origin, DE	-	-	m3	7.31E-1	1	1.22 (2.3.1.1.1.5.BU:1.05); cooling water, from natural origin; de Wild-Scholten, M. 2017. Deliverable 3.1 Life Cycle Analysis of CHEOPS technologies and benchmarking; Screening. Available online.
technosphere	photovoltaic cell, single-Si, at plant	CN	0	m2	9.35E-1	1	1.22 (2.3.1.1.1.5.BU:1.05); Monocrystalline silicon solar cell without the grid, 156mm x 156mm; de Wild-Scholten, M. 2017. Deliverable 3.1 Life Cycle Analysis of CHEOPS technologies and benchmarking; Screening. Available online.
	photovoltaic panel factory	GLO	1	unit	4.00E-6	1	3.05 (2.3.1.1.1.5.BU:3); Factory; de Wild-Scholten, M. 2017. Deliverable 3.1 Life Cycle Analysis of CHEOPS technologies and benchmarking; Screening. Available online.
	electricity, medium voltage, at grid	DE	0	kWh	2.34E+1	1	1.22 (2.3.1.1.1.5.BU:1.05); electricity from external supply; de Wild-Scholten, M. 2017. Deliverable 3.1 Life Cycle Analysis of CHEOPS technologies and benchmarking; Screening. Available online.
	lead, at regional storage	RER	0	kg	1.62E-3	1	1.22 (2.3.1.1.1.5.BU:1.05); Lead iodide; de Wild-Scholten, M. 2017. Deliverable 3.1 Life Cycle Analysis of CHEOPS technologies and benchmarking; Screening. Available online.
	methyl iodide	RER	0	kg	3.94E-4	1	1.22 (2.3.1.1.1.5.BU:1.05); Methyl iodide; de Wild-Scholten, M. 2017. Deliverable 3.1 Life Cycle Analysis of CHEOPS technologies and benchmarking; Screening. Available online.
	ethylene bromide, at plant	RER	0	kg	3.94E-4	1	1.22 (2.3.1.1.1.5.BU:1.05); Ethylene bromide; de Wild-Scholten, M. 2017. Deliverable 3.1 Life Cycle Analysis of CHEOPS technologies and benchmarking; Screening. Available online.
	chemicals organic, at plant	GLO	0	kg	8.13E-5	1	1.22 (2.3.1.1.1.5.BU:1.05); C60 fullerene; de Wild-Scholten, M. 2017. Deliverable 3.1 Life Cycle Analysis of CHEOPS technologies and benchmarking; Screening. Available online.
	chemicals organic, at plant	GLO	0	kg	3.82E-5	1	1.22 (2.3.1.1.1.5.BU:1.05); Spiro-OMeTAD: 2,2',7,7'-Tetrakis-(N,N-di-4-methoxyphenylamino)-9,9'-spirofluorene; de Wild-Scholten, M. 2017. Deliverable 3.1 Life Cycle Analysis of CHEOPS technologies and benchmarking; Screening. Available online.
	solvents, organic, unspecified, at plant	GLO	0	kg	4.24E-1	1	1.22 (2.3.1.1.1.5.BU:1.05); Solvent 1, organic, no halogen containing; de Wild-Scholten, M. 2017. Deliverable 3.1 Life Cycle Analysis of CHEOPS technologies and benchmarking; Screening. Available online.
	solvents, organic, unspecified, at plant	GLO	0	kg	3.94E-2	1	1.22 (2.3.1.1.1.5.BU:1.05); Solvent 2, organic, halogen containing; de Wild-Scholten, M. 2017. Deliverable 3.1 Life Cycle Analysis of CHEOPS technologies and benchmarking; Screening. Available online.
	indium, at regional storage	RER	0	kg	7.50E-3	1	1.22 (2.3.1.1.1.5.BU:1.05); Indium Tin Oxide; de Wild-Scholten, M. 2017. Deliverable 3.1 Life Cycle Analysis of CHEOPS technologies and benchmarking; Screening. Available online.
	tin, at regional storage	RER	0	kg	7.50E-3	1	1.22 (2.3.1.1.1.5.BU:1.05); Indium Tin Oxide; de Wild-Scholten, M. 2017. Deliverable 3.1 Life Cycle Analysis of CHEOPS technologies and benchmarking; Screening. Available online.
	silver, at regional storage	RER	0	kg	3.52E-3	1	1.22 (2.3.1.1.1.5.BU:1.05); Conductive Adhesive: NAMICS H9455: 85-95% Ag, <5% resins (phenolic/epoxy), <5% additives, 5-10% ethylene glycol monophenyl ether (MSDS H9455-21); de Wild-Scholten, M. 2017. Deliverable 3.1 Life Cycle Analysis of CHEOPS technologies and benchmarking; Screening. Available online.
	phenolic resin, at plant	RER	0	kg	9.27E-5	1	1.22 (2.3.1.1.1.5.BU:1.05); Conductive Adhesive: NAMICS H9455: 85-95% Ag, <5% resins (phenolic/epoxy), <5% additives, 5-10% ethylene glycol monophenyl ether (MSDS H9455-21); de Wild-Scholten, M. 2017. Deliverable 3.1 Life Cycle Analysis of CHEOPS technologies and benchmarking; Screening. Available online.
	epoxy resin, liquid, at plant	RER	0	kg	9.27E-5	1	1.22 (2.3.1.1.1.5.BU:1.05); Conductive Adhesive: NAMICS H9455: 85-95% Ag, <5% resins (phenolic/epoxy), <5% additives, 5-10% ethylene glycol monophenyl ether (MSDS H9455-21); de Wild-Scholten, M. 2017. Deliverable 3.1 Life Cycle Analysis of CHEOPS technologies and benchmarking; Screening. Available online.
	diphenylether-compounds, at regional storehouse	RER	0	kg	3.71E-4	1	1.22 (2.3.1.1.1.5.BU:1.05); Conductive Adhesive: NAMICS H9455: 85-95% Ag, <5% resins (phenolic/epoxy), <5% additives, 5-10% ethylene glycol monophenyl ether (MSDS H9455-21); de Wild-Scholten, M. 2017. Deliverable 3.1 Life Cycle Analysis of CHEOPS technologies and benchmarking; Screening. Available online.
	metallization paste, front side, at plant	RER	0	kg	9.38E-3	1	1.22 (2.3.1.1.1.5.BU:1.05); Silver paste; de Wild-Scholten, M. 2017. Deliverable 3.1 Life Cycle Analysis of CHEOPS technologies and benchmarking; Screening. Available online.
	solar glass, low-iron, at regional storage	RER	0	kg	8.13E+0	1	1.22 (2.3.1.1.1.5.BU:1.05); Front glass; de Wild-Scholten, M. 2017. Deliverable 3.1 Life Cycle Analysis of CHEOPS technologies and benchmarking; Screening. Available online.
	tempering, flat glass	RER	0	kg	8.00E+0	1	1.22 (2.3.1.1.1.5.BU:1.05); Tempering, flat glass; de Wild-Scholten, M. 2017. Deliverable 3.1 Life Cycle Analysis of CHEOPS technologies and benchmarking; Screening. Available online.
	flat glass, uncoated, at plant	RER	0	kg	5.08E+0	1	1.22 (2.3.1.1.1.5.BU:1.05); Backside glass; de Wild-Scholten, M. 2017. Deliverable 3.1 Life Cycle Analysis of CHEOPS technologies and benchmarking; Screening. Available online.
	ethylvinylacetate, foil, at plant	RER	0	kg	9.75E-1	1	1.22 (2.3.1.1.1.5.BU:1.05); Ethylvinylacetate foil; de Wild-Scholten, M. 2017. Deliverable 3.1 Life Cycle Analysis of CHEOPS technologies and benchmarking; Screening. Available online.
	copper, at regional storage	RER	0	kg	1.03E-1	1	1.22 (2.3.1.1.1.5.BU:1.05); String copper; de Wild-Scholten, M. 2017. Deliverable 3.1 Life Cycle Analysis of CHEOPS technologies and benchmarking; Screening. Available online.
	wire drawing, copper	RER	0	kg	1.03E-1	1	1.22 (2.3.1.1.1.5.BU:1.05); String copper; de Wild-Scholten, M. 2017. Deliverable 3.1 Life Cycle Analysis of CHEOPS technologies and benchmarking; Screening. Available online.
	tin, at regional storage	RER	0	kg	1.29E-2	1	1.22 (2.3.1.1.1.5.BU:1.05); String tin; de Wild-Scholten, M. 2017. Deliverable 3.1 Life Cycle Analysis of CHEOPS technologies and benchmarking; Screening. Available online.
	lead, at regional storage	RER	0	kg	7.25E-4	1	1.22 (2.3.1.1.1.5.BU:1.05); String lead; de Wild-Scholten, M. 2017. Deliverable 3.1 Life Cycle Analysis of CHEOPS technologies and benchmarking; Screening. Available online.
	1-propanol, at plant	RER	0	kg	1.59E-2	1	1.22 (2.3.1.1.1.5.BU:1.05); Soldering flux propanol; de Wild-Scholten, M. 2017. Deliverable 3.1 Life Cycle Analysis of CHEOPS technologies and benchmarking; Screening. Available online.
	glass fibre reinforced plastic, polyamide, injection moulding, at plant	RER	0	kg	2.95E-1	1	1.22 (2.3.1.1.1.5.BU:1.05); Junction box; de Wild-Scholten, M. 2017. Deliverable 3.1 Life Cycle Analysis of CHEOPS technologies and benchmarking; Screening. Available online.
	diode, unspecified, at plant	GLO	0	kg	2.81E-3	1	1.22 (2.3.1.1.1.5.BU:1.05); Bypass diode; de Wild-Scholten, M. 2017. Deliverable 3.1 Life Cycle Analysis of CHEOPS technologies and benchmarking; Screening. Available online.
	silicone product, at plant	RER	0	kg	1.22E-1	1	1.22 (2.3.1.1.1.5.BU:1.05); Silicone; de Wild-Scholten, M. 2017. Deliverable 3.1 Life Cycle Analysis of CHEOPS technologies and benchmarking; Screening. Available online.
	aluminium alloy, AlMg3, at plant	RER	0	kg	2.13E+0	1	1.22 (2.3.1.1.1.5.BU:1.05); Module frame: aluminium; de Wild-Scholten, M. 2017. Deliverable 3.1 Life Cycle Analysis of CHEOPS technologies and benchmarking; Screening. Available online.
	corrugated board, mixed fibre, single wall, at plant	RER	0	kg	7.63E-1	1	1.22 (2.3.1.1.1.5.BU:1.05); Cardboard for packaging; de Wild-Scholten, M. 2017. Deliverable 3.1 Life Cycle Analysis of CHEOPS technologies and benchmarking; Screening. Available online.
	EUR-flat pallet	RER	0	unit	3.13E-2	1	1.22 (2.3.1.1.1.5.BU:1.05); wooden pallet; de Wild-Scholten, M. 2017. Deliverable 3.1 Life Cycle Analysis of CHEOPS technologies and benchmarking; Screening. Available online.
	transport, freight, lorry, fleet average	RER	0	tkm	4.61E+0	1	2.05 (2.3.1.1.1.5.BU:2); Transport lorry; de Wild-Scholten, M. 2017. Deliverable 3.1 Life Cycle Analysis of CHEOPS technologies and benchmarking; Screening. Available online.
	transport, transoceanic freight ship	OCE	0	tkm	6.14E+1	1	2.05 (2.3.1.1.1.5.BU:2); Transport ship; de Wild-Scholten, M. 2017. Deliverable 3.1 Life Cycle Analysis of CHEOPS technologies and benchmarking; Screening. Available online.
	disposal, plastics, mixture, 15.3% water, to municipal incineration	CH	0	kg	3.02E-2	1	1.22 (2.3.1.1.1.5.BU:1.05); EVA cutting loss; de Wild-Scholten, M. 2017. Deliverable 3.1 Life Cycle Analysis of CHEOPS technologies and benchmarking; Screening. Available online.
	disposal, solvents mixture, 16.5% water, to hazardous waste incineration	CH	0	kg	8.86E-1	1	1.22 (2.3.1.1.1.5.BU:1.05); organic solvent (halogen free), halogen containing solvent, PB + halogen containing solvent; de Wild-Scholten, M. 2017. Deliverable 3.1 Life Cycle Analysis of CHEOPS technologies and benchmarking; Screening. Available online.
emission air, high population density	Lead	-	-	kg	1.16E-5	1	5.06 (2.3.1.1.1.5.BU:5); Lead to air; de Wild-Scholten, M. 2017. Deliverable 3.1 Life Cycle Analysis of CHEOPS technologies and benchmarking; Screening. Available online.
emission water, unspecified	Lead	-	-	kg	1.16E-5	1	5.06 (2.3.1.1.1.5.BU:5); Lead to water; de Wild-Scholten, M. 2017. Deliverable 3.1 Life Cycle Analysis of CHEOPS technologies and benchmarking; Screening. Available online.
emission air, high population density	Water	-	-	kg	3.66E+1	1	1.58 (3.3.1.1.1.5.BU:1.5); Cooling water emissions (5% of used cooling water); Estimated based Frischknecht and Büsser (2013)

To compare the environmental impacts of the perovskite silicon tandem PV panel with the impacts of a single crystalline silicon PV panel, the generic dataset for the production of a single crystalline silicon PV panel in Europe (Frischknecht et al. 2015a) was adapted. Instead of the production mix for PV single crystalline silicon cells, PV single crystalline silicon cells produced in China were used. Furthermore the transport of these cells to Europe was added according to the transport distances published by de Wild-Scholten (2017).

4 Life cycle impact assessment

4.1 Overview

In this chapter the environmental impacts of 1 m² perovskite silicon tandem PV panel and 1 m² single crystalline silicon PV panel are quantified and the most relevant processes are identified. The environmental impacts are additionally assessed using the EF impact assessment method (Fazio et al. 2018). The results of this assessment are presented in Subchapter 4.2 (single score) and 4.3 (midpoints). Furthermore the non-renewable and renewable cumulative energy demand (Frischknecht et al. 2015b) was quantified and is presented in Subchapter 4.4. The ILCD Midpoint 2011 method (European Commission et al. 2012) is used to discuss the data quality (see Subchapter 4.5).

4.2 EF method - Single score

In Figure 4-1 the total environmental impacts (single score) of the production of 1 m² perovskite silicon tandem PV panel and 1 m² single silicon PV panel quantified according the EF method and the normalization and weighting factors described in European Commission (2017) are presented. The three toxicity related impact categories were excluded (see subchapter 2.4).

The total environmental impacts of the perovskite silicon tandem PV panel are 64.5 milli-points (mPt)/m². The impact category “Resource use, mineral and metals” contributes with 48 % the most to the overall impacts. Further relevant impact categories are “Climate Change” (18 %) and “Respiratory inorganics” (12 %). The total environmental impacts of the single crystalline silicon PV panel are 44.75 mPt/m² or about 28 % lower than the environmental impacts of the perovskite silicon tandem PV panel. In Table 4-1 the normalized and weighted environmental impacts of the quantified midpoint categories are shown for both panels.

Table 4-1: Normalized and weighted environmental impacts of the production of 1 m² perovskite silicon tandem PV panel produced in Germany and of 1 m² single crystalline silicon PV panel produced in Europe in milli-points per m² PV panel according to the EF impact assessment method (excluding toxicity impacts, excluding long-term emissions).

Impact category	Perovskite silicon tandem PV panel		Single crystalline silicon PV panel	
	(mPt/m ²)	%	(mPt/m ²)	%
Climate change	11.49	18%	11.12	25%
Ozone depletion	0.04	0%	0.03	0%
Ionising radiation, HH	0.13	0%	0.12	0%
Photochemical ozone formation, HH	1.73	3%	1.70	4%
Respiratory inorganics	7.74	12%	7.67	17%
Acidification terrestrial and freshwater	4.33	7%	4.24	9%
Eutrophication freshwater	0.25	0%	0.18	0%
Eutrophication marine	0.54	1%	0.52	1%
Eutrophication terrestrial	1.08	2%	1.04	2%
Land use	0.09	0%	0.10	0%
Water scarcity (adapted)	0.84	1%	0.82	2%
Resource use, energy carriers	5.48	9%	5.20	12%
Resource use, mineral and metals	30.72	48%	12.02	27%
Total	64.46	100%	44.75	100%

The two largest contributors to the total environmental impacts of the perovskite silicon tandem PV panel are the production of the single crystalline silicon PV cell in China (63 %) and the production of the metallization paste (20 %) (see Figure 4-1). The largest contributor to the environmental impact of the single crystalline silicon PV panel is the production of the single crystalline silicon PV cell in China (91 %).

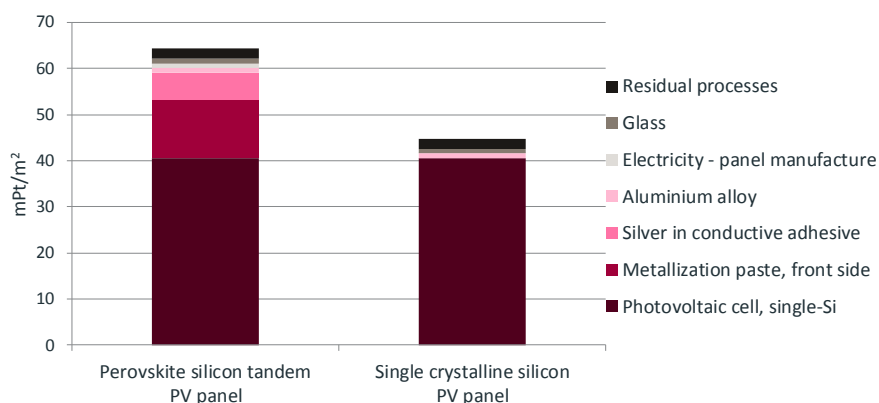


Figure 4-1: Single score environmental impact quantified according the EF method of the production of 1 m² perovskite silicon tandem PV panel in Germany and 1 m² single crystalline silicon PV panel in Europe.

4.3 EF method - Midpoints

In Table 4-2 the impact indicators quantified according the EF impact assessment method (excluding toxicity impact categories) are shown. The grey shaded impact categories are further analysed by identifying the most important contributors.

Table 4-2: Characterised environmental impacts of the production of 1 m² perovskite silicon tandem PV panel produced in Germany and 1 m² single crystalline silicon PV panel produced in Europe according to the EF impact assessment method.

Impact category	Unit/m ²	Perovskite silicon tandem PV panel	Single crystalline silicon PV panel
Climate change	kg CO ₂ eq	401.8	388.9
Ozone depletion	µg CFC11 eq	14.3	9.0
Ionising radiation, HH	kBq U-235 eq	10.3	9.6
Photochemical ozone formation, HH	g NMVOC eq	1'377.9	1'349.8
Respiratory inorganics	micro disease inc.	51.6	51.2
Acidification terrestrial and freshwater	mol H+ eq	3.6	3.5
Eutrophication freshwater	g P eq	21.7	15.5
Eutrophication marine	g N eq	486.4	475.0
Eutrophication terrestrial	mol N eq	4.9	4.7
Land use	Pt	1'467.6	1'583.4
Water scarcity (adapted)	m ³ water eq	106.6	103.5
Resource use, energy carriers	MJ oil eq	4'010.8	3'803.3
Resource use, mineral and metals	g Sb eq	22.0	8.6

The production of 1 m² perovskite silicon tandem PV panel emits 402 kg CO₂-eq of greenhouse gases (GHG) per m² PV panel. 85 % of the emissions are caused by the production of the single crystalline silicon PV cell in China (see Figure 4-2). A reason for this high contribution is the Chinese electricity mix, which contains a high share of electricity produced by hard coal power plants. Further minor contributors to the total GHG emissions are the production of the aluminium used for the panel frame (4 %), the electricity used for the production of the perovskite silicon tandem panel (4 %), the production of the front and back glass (3 %) and the production of the ethylene-vinyl-acetate foil used for the encapsulation (1 %). The production of 1 m² single crystalline silicon PV panel emits 3 % less GHG emissions than the production of the perovskite silicon tandem PV panel. The GHG emissions of the production of 1 m² single silicon PV panel are 389 kg CO₂-eq per m².

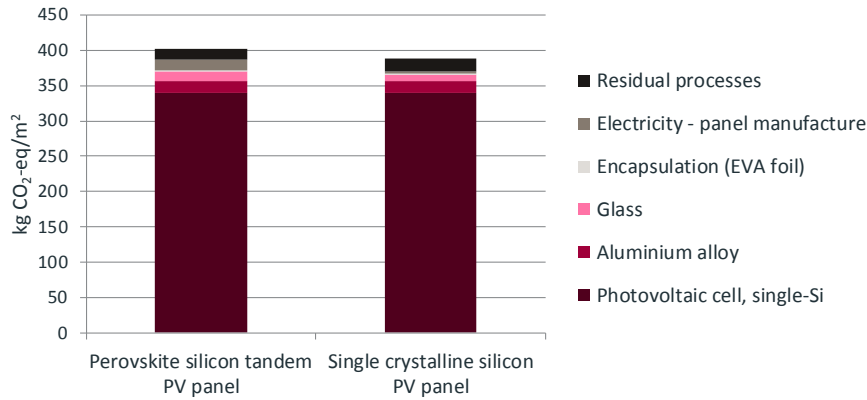


Figure 4-2: Climate change impact of the production of 1 m² perovskite silicon tandem PV panel in Germany and 1 m² single crystalline silicon PV panel in Europe quantified in kg CO₂-eq according to the EF impact assessment method.

The respiratory effects of the production of 1 m² perovskite silicon tandem PV panel quantified in micro disease incidences are 51.6. The production of the single crystalline silicon photovoltaic cell in China is mainly responsible for the impacts, which contributes 95 % to the total respiratory effects. The respiratory effects caused by the production of 1 m² single crystalline silicon PV panel are 1 % lower compared to those caused by the production of 1 m² perovskite silicon tandem PV panel. The distribution of the shares of the different processes is shown in Figure 4-3.

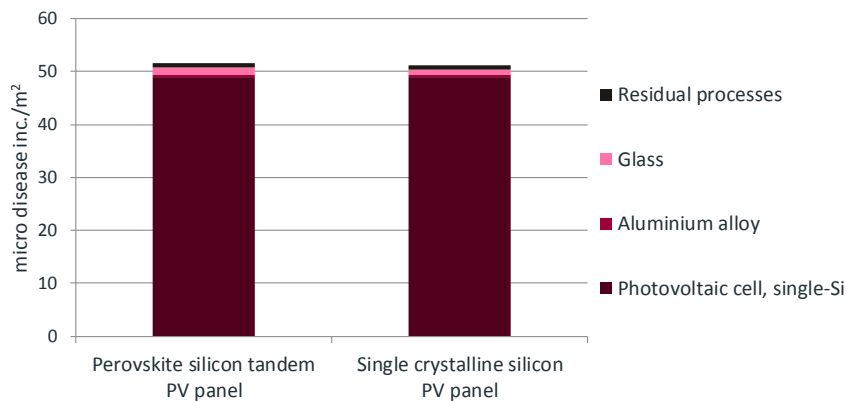


Figure 4-3: Respiratory effects of the production of 1 m² perovskite silicon tandem PV panel and 1 m² single crystalline silicon PV panel in Europe quantified in micro disease incidences according to the EF impact assessment method.

The acidification (terrestrial and freshwater) impact of the production of perovskite silicon tandem PV panel is 3.6 mol H⁺-eq/m². As for the impact categories “Climate Change” and “Respiratory inorganics”, the production of the single crystalline silicon photovoltaic cell is the major contributor (89 %) to acidification impacts too (see Figure 4-4). The acidification (terrestrial and freshwater) impact of the production of a single

crystalline silicon PV panel is 3.5 mol H⁺-eq/m² and thus 2 % lower than the acidification impact of the perovskite silicon tandem PV panel.

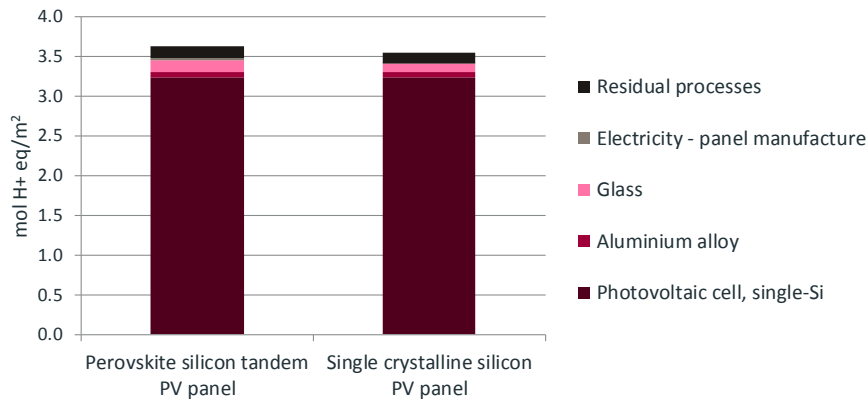


Figure 4-4: Acidification (terrestrial and freshwater) impact of the production of 1 m² perovskite silicon tandem PV panel in Germany and 1 m² single crystalline silicon PV panel in Europe quantified in mol H⁺-eq according to the EF impact assessment method.

The resource use of energy carriers is 4'009 MJ oil equivalents per m² perovskite silicon tandem PV panel produced. The major contributor is the production of the photovoltaic cell (79 %). The second largest contributor is the electricity use during panel production (6 %). The production of aluminium (4 %), front and back glass (4 %) and ethylene-vinyl-acetate foil (2%) are further minor contributors to the resource use of energy carriers. The resource use of energy carriers for the production of 1 m² single crystalline silicon PV panel is 3'800 MJ oil eq and thus 5 % lower than the resource use of energy carriers per m² perovskite silicon tandem PV panel produced. In Figure 4-5 the different shares of the production processes to the resource use of energy carriers are shown.

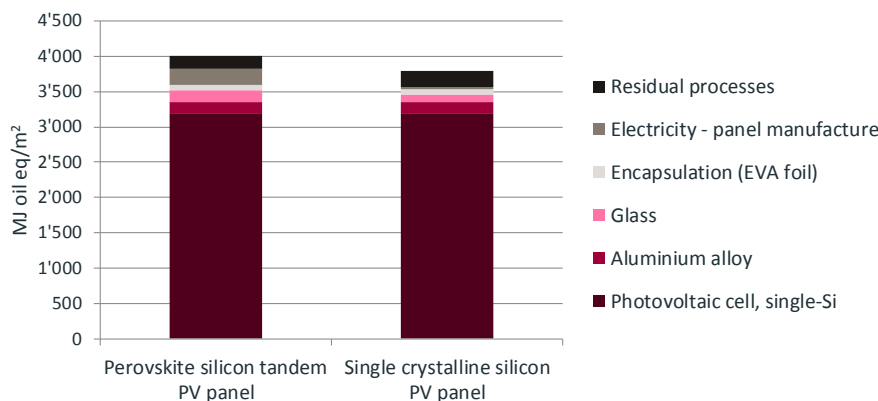


Figure 4-5: Resource use, energy carriers impact of the production of 1 m² perovskite silicon tandem PV panel in Germany and 1 m² single crystalline silicon PV panel in Europe quantified in MJ oil eq according to the EF impact assessment method.

In Figure 4-6 the impact of the production of 1 m² perovskite silicon tandem PV panel and 1 m² single silicon PV panel on mineral and metal resource depletion is shown. The total impact is 22 g Sb-eq/m² for the perovskite silicon tandem PV panel and 9 g Sb-eq/m² for the single crystalline silicon PV panel. Different to the other impact categories, the main contributor in the production of the perovskite silicon tandem PV panel is the production of the metallization paste with a share of 41 % in the total mineral and metal resource impacts. This is mainly due to silver used in the metallization paste and the corresponding extraction of silver resources. Other main contributors are the production of the photovoltaic cell (37 %) and the silver which is used in the conductive adhesives (19 %). As less silver is used the production of the single crystalline silicon PV panel the resource use impact is 61 % lower compared to the resources use impact of the perovskite silicon tandem PV panel.

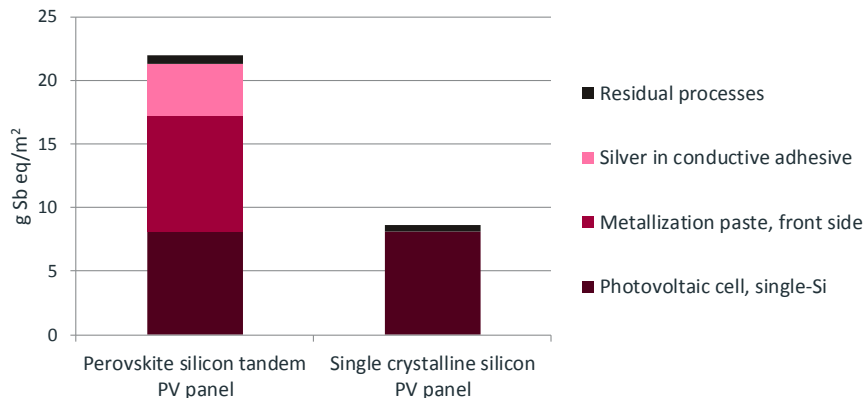


Figure 4-6: Resource use, mineral and metals impact of the production of 1 m² perovskite silicon tandem PV panel in Germany and 1 m² single crystalline silicon PV panel in Europe quantified in g Sb-eq according to the EF impact assessment method.

4.4 Cumulative energy demand – non-renewable and renewable

The non-renewable cumulative energy demand (CED) of the production of 1 m² perovskite silicon tandem PV panel is 4243 MJ oil-eq (see Figure 4-7). 79 % of the non-renewable CED is caused by the production of the single crystalline silicon photovoltaic cell in China. This is mainly due to the hard coal dominated electricity mix of China. With 6 % the electricity use during the production of the perovskite silicon tandem PV panel is the second largest contributor. The production of aluminium (4 %), front and back glass (4 %) and the EVA foil (2 %) are only minor contributors to the non-renewable CED. The non-renewable CED of the production of 1 m² single crystalline silicon PV panel is 4'021 MJ oil-eq and thus 5 % lower compared to the non-renewable CED of the production of 1 m² perovskite silicon tandem PV panel. The difference is mainly due to the different amount of electricity used during the manufacturing of the panel.

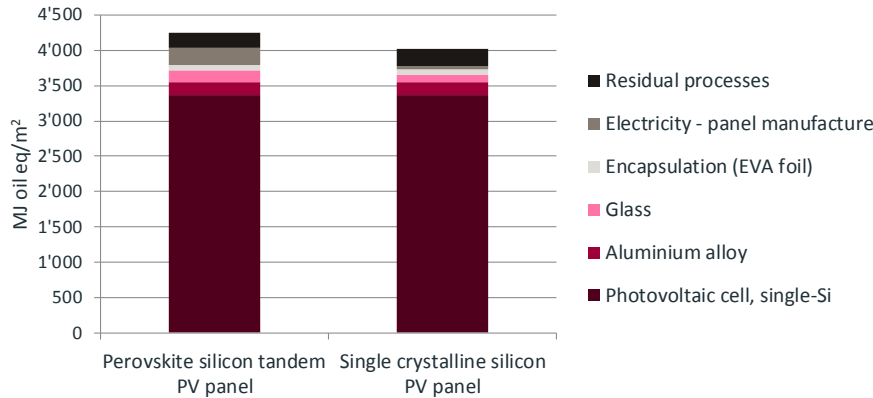


Figure 4-7: CED, non-renewable of the production of 1 m² perovskite silicon tandem PV panel and 1 m² single crystalline silicon PV panel in Europe quantified in MJ oil-eq according to Frischknecht et al. (2015b).

In Figure 4-8 the renewable CED of the production of 1 m² perovskite silicon tandem PV panel and 1 m² single crystalline silicon PV panel is shown. The total renewable CED is 485 MJ oil-eq/m² perovskite silicon tandem PV panel. The production of the photovoltaic cell in China is mainly responsible for the renewable CED with a contribution of 79 %. The second largest contributor is the production of aluminium with a share of 10 %. The packaging (wood pallet and cardboard, 4 %) and the electricity use during production of the photovoltaic panel (3 %) are further minor contributors to the renewable CED of the production of 1 m² perovskite silicon tandem PV panel. The renewable CED of the production of 1 m² single crystalline silicon PV panel is 479 MJ oil eq/m² and thus 1 % lower compared to the renewable CED of the production of perovskite silicon tandem PV panels.

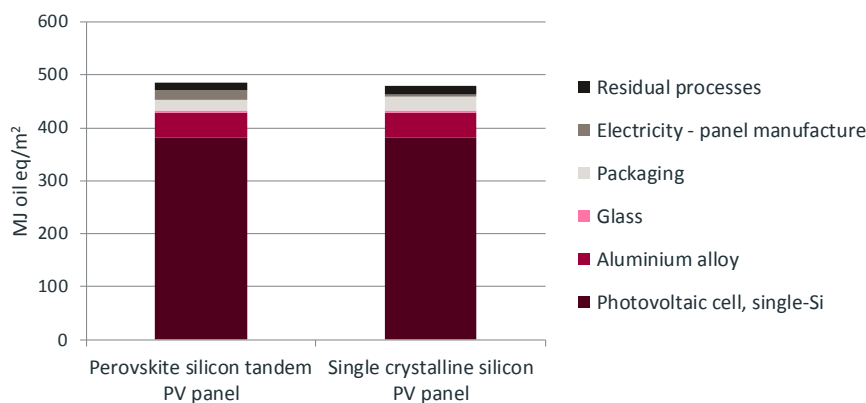


Figure 4-8: CED, renewable of the production of 1 m² perovskite silicon tandem PV panel and 1 m² single crystalline silicon PV panel in Europe quantified in MJ oil-eq according to Frischknecht et al. (2015b).

4.5 Data quality considerations

The plausibility of the impact assessment results of 1 m² perovskite silicon tandem PV panel was checked by comparing the results according to the ILCD Midpoint 2011 method (European Commission et al. 2012) with the results published in de Wild-Scholten (2017). The comparison revealed that the characterised environmental impacts for selected midpoints are 25 % (Human toxicity – cancer effects) to 67 % (climate change) higher than the results reported by de Wild-Scholten (2017). The main reasons for these differences are the use of an updated confidential LCI for the production of the photovoltaic single crystalline silicon cell in China by de Wild-Scholten (2017) and differences in the background data (ecoinvent data v3.3 compared to UVEK LCI data DQRv2:2018), particularly with regard to the supply of aluminium alloy for the module frame and of silver used in the metallization paste.

5 Conclusions

The assessment of the production of 1 m² perovskite silicon tandem PV panel with the normalized and weighted EF method (Fazio et al. 2018) without toxicity categories showed that the impact categories “Resource use, mineral and metals”, “Climate Change”, “Respiratory inorganics”, “Resource use, energy carriers” and “Acidification terrestrial and freshwater” contribute the most to the overall environmental impact. In all these impact categories except “Resource use, mineral and metals” the production of the single crystalline silicon photovoltaic cell in China is the major contributor to the environmental impact. The reason for the high contribution of the single crystalline silicon cell is the high share of hard coal power plants in the Chinese electricity mix and the high electricity demand in the supply of single crystalline silicon ingot. For the impact category “Resource use, mineral and metals” the production of the metallization paste is mainly responsible for the resource depletion of mineral and metals. The assessment showed, that the environmental impacts of the production of perovskite silicon tandem PV panels are driven by processes upstream in the PV supply chain (such as the production of the single crystalline silicon PV cell) and not the materials used to produce the perovskite composition. The electricity use during production of the perovskite PV panel is the only input, that has a share up to 6 % in some impacts category.

The comparison of the environmental impacts of the production of 1 m² perovskite silicon tandem PV panel and 1 m² single crystalline silicon PV panel revealed that in all selected midpoint categories the production of single crystalline silicon PV panel has lower impacts. The environmental impacts differ between 1 % (respiratory effects) to 5 % (resource use, fossil fuels), except for resource use, mineral and metal with a difference of 61 %. Hence, the perovskite silicon tandem PV panel would need to be 1 % to 5 % more efficient than the single crystalline silicon PV panel to have a similar environmental impact per kWh produced, disregarding mineral resource use impacts.

References

- accelopment AG (2016) CHEOPS - Project Factsheet.
- Battaglia C., Cuevas A. and De Wolf S. (2016) High-efficiency crystalline silicon solar cells: status and perspectives. In: *Energy Environ. Sci.*, 9, pp. 1552–1576.
- de Wild-Scholten M. (2017) Deliverable 3.1 - Life Cycle Analysis of CHEOPS technologies and benchmarking: Screening.
- ecoinvent Centre (2010) ecoinvent data v2.2, ecoinvent reports No. 1-25. Swiss Centre for Life Cycle Inventories, Duebendorf, Switzerland, retrieved from: www.ecoinvent.org.
- ecoinvent Centre (2016) ecoinvent data v3.3. ecoinvent Association, Zürich, Switzerland, retrieved from: www.ecoinvent.org.
- European Commission, Joint Research Centre and Institute for Environment and Sustainability (2012) Characterisation factors of the ILCD Recommended Life Cycle Impact Assessment methods. Database and Supporting Information. First Edition. Publication Office of the European Union, Luxembourg.
- European Commission (2017) PEFCR Guidance Document - Guidance for the development of Product Environmental Footprint Category Rules (PEFCRs), version 6.3, December 2017. European Commission.
- Fazio S., Biganzioli F., De Laurentiis V., Zampori L., Sala S. and Diaconu E. (2018) Supporting information to the characterisation factors of recommended EF Life Cycle Impact Assessment methods, version 2, from ILCD to EF 3.0. PUBSY No. JRC114822. European Commission, Ispra.
- Frischknecht R. and Büsser Knöpfel S. (2013) Swiss Eco-Factors 2013 according to the Ecological Scarcity Method. Methodological fundamentals and their application in Switzerland. Environmental studies no. 1330. Federal Office for the Environment, Bern, retrieved from: <http://www.bafu.admin.ch/publikationen/publikation/01750/index.html?lang=en>.
- Frischknecht R., Itten R., Sinha P., de Wild Scholten M., Zhang J., Fthenakis V., Kim H. C., Raugei M. and Stucki M. (2015a) Life Cycle Inventories and Life Cycle Assessments of Photovoltaic Systems. International Energy Agency (IEA) PVPS Task 12.
- Frischknecht R., Wyss F., Büsser Knöpfel S., Lützkendorf T. and Balouktsi M. (2015b) Cumulative energy demand in LCA: the energy harvested approach. In: *The International Journal of Life Cycle Assessment*, 20(7), pp. 957-969, 10.1007/s11367-015-0897-4, retrieved from: <http://dx.doi.org/10.1007/s11367-015-0897-4>.
- Itten R. and Stucki M. (2017) Highly Efficient 3rd Generation Multi-Junction Solar Cells Using Silicon Heterojunction and Perovskite Tandem: Prospective Life Cycle Environmental Impacts. In: *Energies*, 10(7), pp. 841.
- KBOB, eco-bau and IPB (2018) UVEK Ökobilanzdatenbestand DQRv2:2018. Koordinationskonferenz der Bau- und Liegenschaftsorgane der öffentlichen Bauherren c/o BBL Bundesamt für Bauten und Logistik, retrieved from: www.ecoinvent.org.
- PRé Consultants (2018) SimaPro 8.5.2, Amersfoort, NL.

Sahli F., Werner J., Kamino B., Bräuninger M., Monnard R., Paviet-Salomon B., . and Ballif C. (2018) Fully textured monolithic perovskite/silicon tandem solar cells with 25.2% power conversion efficiency. In: Nature Materials, 17(9), pp. 820-826.

TS PEF Pilot PV (2018) Product Environmental Footprint Category Rules (PEFCR): Photovoltaic Modules used in Photovoltaic Power Systems for Electricity Generation. treeze Ltd., commissioned by the Technical Secretariat of the PEF Pilot "Photovoltaic Electricity Generation", Uster, Switzerland.