Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 69 (2018) 389 – 394

www.elsevier.com/locate/procedia

25th CIRP Life Cycle Engineering (LCE) Conference, 30 April – 2 May 2018, Copenhagen, Denmark

Taking evolution into account in a parametric LCA model for PV panels

Ellen Bracquene[a,]*, Jef R. Peeters[a], Wim Dewulf[a],Joost R. Duflou[a]

[a]*KU Leuven Mechanical Engineering Department, Celestijnenlaan 300, Heverlee 3001,, Belgium*

* Corresponding author. Tel.: +32 16 32 25 67; fax: +32 16 32 29 86. *E-mail address:* ellen.bracquene@kuleuven.be

---

Abstract

Over the last decade the environmental impact of photovoltaic (PV) panels has extensively been explored, often using a Life Cycle Assessment (LCA) methodology. However, the manufacturing data in reference databases are typically outdated and the end-of-life treatment is mostly omitted from the scope of these studies. The objective of the current study is to inform decision-makers about potential environmental impact reductions, mostly through dematerialization of the manufacturing phase and secondary material recovery at end-of-life. The results show how taking into account eco-design aspects in the manufacturing stage and a well-designed end-of-life treatment system can further contribute to lowering the environmental impact of PV panels and thus renewable energy production.

Keywords: Renewable Energy; Photovoltaic Panels; LCA; Ecodesign; Recycling

---

1. Introduction

Over the last decades the use of photovoltaic (PV) panels for electricity production has rapidly increased. In 2015, the cumulative installed capacity of PV panels exceeded 200 GW by the end of the year, with an increase in installed capacity that was 25% higher than in 2014 [1]. Even though other technologies have been introduced, such as thin-film PV, crystalline Silicon (c-Si) modules still dominate the PV market with around 90% of the installed capacity in 2015 [2,5,23]. In recent years the cost of c-Si PV panel production has substantially dropped in consequence of technological improvements combined with low material costs for Silicon [1,3-6].

The environmental impact assessment of PV panels is commonly performed in a cradle to gate approach, and the end-of-life (EoL) treatment is thus typically omitted from the study boundary [7,8]. Although recycling of PV panels has already been explored and innovative recycling approaches have been investigated [9-13], the potential environmental impact of EoL has not been fully integrated in the lifecycle impact assessment of PV panels. Life Cycle Assessment (LCA) impact studies have focused on embedded energy and greenhouse gas emissions, and thus other impact categories, such as resource depletion, have mostly been neglected. Finally, the influence of technological developments over time on the environmental performance of PV panels has not yet been fully investigated.

2. Life cycle assessment - LCA

The objective of the current study is to inform decision-makers about potential environmental impact reductions for PV panels. Using a parametric LCA model, the study takes global technological trends into account in order to gain insight in most likely future scenarios. The model is built using SimaPro 8.3 as software tool and ecoinvent 3.3 as reference database. The “allocation default” system model is used because, for attributional LCA, partitioning is recommended when dealing with multi-functionality if it cannot be avoided [14].

doi:10.1016/j.procir.2017.11.103

In this study, the lifecycle of PV panels is taken into account from raw material extraction up to the end-of-life (EoL) treatment, as shown in Figure 1. However, the use phase is not included because the electricity generation of the PV system is highly case specific. Therefore, the Balance of System (BoS) components, such as inverters, charge controllers, batteries and mounting structures, have been omitted from the system boundary. As shown in Figure 1, only recovered material that can be reused in the same product system is considered. Secondary materials, potentially downgraded to other product systems, are not considered.

Although former LCA studies on PV panel have often reported the environmental impact per kWh, in this study the reference flow is Wp because the electricity generation is highly influenced by external factors. Furthermore, the results expressed per Wp can easily be translated to kWh for a specific case with the following formula:

$$CF = \frac{Irr\,.LT.PR\,.Mod_{eff}}{d} \quad (1)$$

With: CF = conversion factor
Irr = irradiation expressed in kWh/(m².year)
LT = lifetime expressed in year
PR = performance ratio (system efficiency)
Mod_{eff} = module efficiency
d = panel capacity expressed in Wp/m²

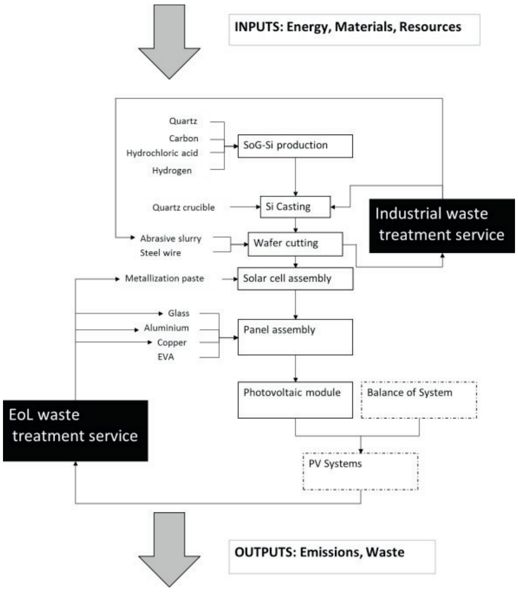

Fig. 1. System boundary for lifecycle of PV panel.

In order to compare our results with previously published results, both the potential impact on climate change expressed in kg CO_2 equivalents [42] and Cumulative Energy Demand (CED) expressed in MJ [43] will be calculated. Climate changes factors with a time horizon of 100 years are used. Additionally the Europe Recipe H/A method [15] is used to quantify the potential environmental impact for a wide range of impact categories, including climate change, human toxicity, particular matter formation, land occupation and resource depletion.

3. Photovoltaic panel products - Evolution

3.1. Evolution in technology

Although multi-crystalline Silicon (mc-Si) solar cells are known to have a lower efficiency than single-crystalline (sc-Si) cells, they have remained popular as they are less expensive to produce, representing almost 70% of global PV module production in 2016 [5,24]. If produced at large scale, thin-film solar cells could potentially be even less expensive to manufacture than mc-Si cells, however they have not yet managed to match the commercial conversion efficiencies achieved by crystalline technologies. Additionally the use of rare earth elements, with potentially unstable supplies, also hampers increase in large scale production resulting in a limited market share of 10% over the last 5 years. Organic thin-film PV cells are still in an early development stage and have not yet resulted in stable market products. Solar cells are combined together in PV modules with a typical capacity between 150 - 350 W. Modules with a higher capacity have been developed for specific building-integrated PV systems (BIPV) [5,25]. PV modules are combined with BoS components to form a PV System.

3.2. Evolution in manufacturing

As described in the previous section, Silicon based PV technology dominates the current PV market. Therefore this section describes recent evolution in mc-Si PV panel production.

Metallurgical Grade Silicon (MG-Si) is produced from quartz reduction at high temperature. Before the MG-Si can be used as semiconductor, it needs to be further purified. Depending on the impurity level it will be named Solar Grade Silicon (SoG-Si) or Electronic Grade Silicon (EG-Si). Because the impurity requirements for PV applications are less stringent, the PV industry mainly relied on the ‘off-grade’ Silicon from electronics until around 2000. Due to increasing demand, different technologies have been developed to produce SoG-Si from MG-Si directly. Nowadays most SoG-Si manufacturers use modified Siemens or Fluidized bed reactor (FBR) processes. The production efficiency of these conventional technologies have improved significantly in recent years, which also has been reflected by a reduction in Silicon market value [4]. Energy consumption in 2015 reached less than 55 kWh/kg compared to 80 kWh/kg in 2010 [5]. Current available lifecycle inventory (LCI) databases still assume 110 kWh/kg [27]. Furthermore, according to a manufacturer in Norway, innovative production processes are commercially available with even lower energy requirements of around 11 kWh/kg [26].

The SoG-Si is molten and casted into crucibles. When crystalline blocks are sawn into thin wafers, the cuttings, including broken wafers, are partly reused as input. Both Silicon Carbide (SiC) and Polyethyleengycol (PEG) are recycled from the abrasive cutting slurry. This is mostly done off site by the slurry provider and typical recycling rates are 80-

90%. An alternative wafer cutting technique is to replace the steel wire by a diamond-plated wire and the abrasive slurry by a cooling liquid. Even though the diamond wire sawing provides advantages, such as higher productivity and reduced wear losses compared to the steel wires, slurry based wafer sawing will most likely remain the dominant technology [4]. In 2015, it has been reported that on average 5,6 g of SoG-Si is used per Wp of solar cell [5]. This represents a reduction of 65% compared to the polysilicon usage in 2004 (16 g Si/Wp). The reduction is due to thinner wafers on the one hand (from 300 µm to 180 µm), reduced kerf losses and increased SoG-Si recycling. New wafer manufacturing techniques, such as kerfless technologies, have been developed in order to further increase the Silicon efficiency. Despite promising results reported by both academia and industry [28-30], these techniques are not expected to gain a market share exceeding 5% in the coming years [4].

Metallization is an important processing step because it has an important influence on the efficiency and performance of the solar cell. Screen printed metallization is the main technique used in industry due to its simplicity, process speed and cost [31]. The Silver content of the metallization paste has decreased over the last decade, mainly due to the related cost. Between 2010 and 2015, the amount of Silver per Wp has been reduced with almost 67% [32,33]. Although reduction has become increasingly challenging, the amount of Silver used in the solar cells is expected to further decrease in the coming years [34].

The electricity used for the solar cell production has significantly been reduced from almost 30 kWh/m² in 2006 to less than 15 kWh/m² in 2011 [20,36].

The most energy intensive production steps are the SoG-Si production and the solar cell manufacturing. Although Europe and the U.S. dominated the PV manufacturing industry in early years, today almost 50% of the SoG-Si and 80% of the solar cell are produced in Asia [34].

3.3. Evolution in end of life management

Today, the waste stream resulting from PV systems is still limited, but is expected to gain more importance in the near future as more PV installations reach their end of life [9,32]. Initially the PV waste stream will most likely be treated in a similar way as other electronic waste. Material will be separated through conventional recycling techniques, such as size-reduction with a shredder followed by magnetic and eddy-current separation, yielding low quality secondary material due to impurities, limited separation efficiencies and presence of hazardous compounds [35]. Although innovative processes are being researched for Silicon based PV panels [9-11], currently only a limited amount of valuable secondary material is recovered and reused [12,13]. In the meanwhile, more efficient and innovative separation techniques have been developed for thin film PV panels by the German company *Loser Chemie* and U.S.-based manufacturer *First Solar*. As waste volumes and raw material cost increase and material efficiency policies are further implemented, it is expected that PV waste will be treated with improved separation technology to enable higher recovery rates and improved secondary material quality.

4. Photovoltaic panel products - previous LCA studies

Over the last decades the environmental impact of photovoltaic (PV) panels has been extensively explored using the Life Cycle Assessment (LCA) methodology. The reported value for Cumulative Energy Demand (CED) ranges between 20 and 35 MJ/Wp [8,16,17,36-39]. From this range the lower value corresponds to more recent studies [37-39] and this reduced energy demand can be mostly attributed to an increased PV capacity (Wp) per m^2. The comparison of Global Warming Potential (GWP) results is less straightforward because it is typically expressed in $kgCO_2e/kWh$ and the electricity production of PV panels highly depends on the assumed location (irradiation), performance ratio, module efficiency, expected life time and PV capacity (Wp/m²).

The reported GWP results over the last two decades mostly fall within the range of 1-4 $kgCO_2e/Wp$ [8,16-18,21,36-41]. Some recent studies take the actual electricity mix at the production site location into account, resulting in relatively high carbon footprint results per m^2. For example, *Pacca et al* assume the PV panels are made in the U.S. while *Desderi et al* assume electricity usage for panel production is taken from the Chinese grid [17,18]. However, both studies show a lower potential impact on climate change when expressing the results in gCO_2e per kWh because of the relatively high annual electricity production [17] or Wp/m² ratio [18] that has been assumed. On the other hand, some recent studies take increased efficiencies that have been made along the PV panel supply chain into account. For example, *Stoppato et al* take an increased energy efficiency into account for the transformation of MG-Si to SoG-Si [19] while *Sagani et al* include the recycling of SiC (80%) and PEG (95%) used in sawing fluids. However when expressed in kWh the result of *Sagani's* study shows a relatively high environmental impact because the annual electricity production is assumed to be rather low, which is partly due to the limited irradiation assumed in his study [40].

Some studies include decommissioning at the end of the use phase, but they exclude further waste treatment or recycling activities [20,21]. One study includes both take back and recycling activities, while also awarding credits for avoided primary material production [22]. Because this study only reports an aggregated result and because the assumptions regarding the avoided primary material are not disclosed, the overall contribution of the EoL stage is not clear. All other analysed studies exclude EoL treatment of PV panels.

Even though the results are difficult to compare because of different system boundaries, environmental impact models and assumptions, the analysis is still useful to gain more insight in typical parameters that influence the environmental performance of PV panel.

5. LCA Results

A parametric LCA model was built to calculate the potential environmental impact of PV modules over time taking technological evolution into account. In this chapter the model parameters and their evolution over time are discussed in subsection 5.1. The environmental impact assessment results are described in subsection 5.2 and further analyzed in subsection 5.3.

5.1. Inventory analysis

As discussed in the previous section, a number of technological improvements and material efficiency measures have taken place at various stages of the PV life cycle.

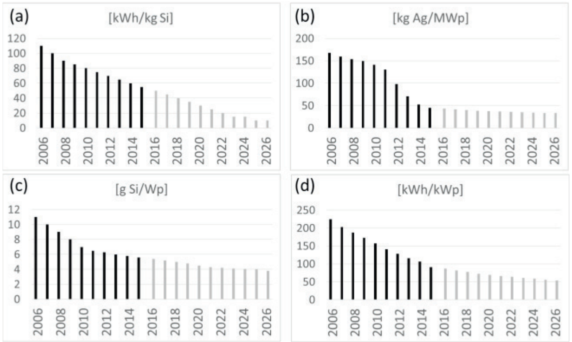

Fig. 2. (a) Electricity usage Silicon production; (b) Silver usage in solar Cell production; (c) Silicon usage for wafer production; (d) Electricity usage for solar cell production.

Based on these industry reports, combined with existing LCI inventories, the evolution for a number of parameters was mapped between 2006 and 2015 and extrapolated until 2026. The results for the most relevant parameters are shown in Figure 2. These parameters are used to build a parametric LCA model for PV panels as a function of the production year.

The future electricity requirements for Silicon production have been estimated based on the observed previous trend and state of the art technology [26]. The Silver usage for solar cell production and Silicon usage for wafer production are estimated based on predicted evolution in trend reports [4-5,33]. The electricity usage for solar cell production after 2015 has been estimated based on the observed previous trend taking into account that further reduction will become increasingly challenging.

To evaluate the end of life of the PV panels, several end of life options are considered. Until 2007, it is assumed that PV panels are treated together with other electronic waste. The LCI data for this process is available in ecoinvent. Between 2007 and 2020, the aluminium frame is manually removed allowing for full recovery and reuse of the aluminium resources. After 2020, improved recycling technology is assumed to be implemented allowing solar glass, Silver and Copper to be recovered and reused as well. Limited data is available for such innovative recycling process, however the LCI data published by *Latunussa et al* is used to estimate the potential environmental impact [9].

Background system, such as changing electricity mixes by 2026, have not been taken into account in our model. However, the influence of the electricity mix decreases as the energy intensity of the production phase declines over time.

5.2. Impact assessment

Based on the LCI parameters assumed for 2016, the GWP of an average m-Si PV panel is 1,12 kg CO_2e/Wp while the CED amounts to 15,83 MJ/Wp. In the next section these results are compared to previously published LCA results.

Figure 3 shows the normalized potential environmental impact using the Europe ReCiPe H/A method for each impact category. The relatively higher impacts for human toxicity and marine ecotoxicity are mostly due to the extraction of Copper.

Figure 5 shows the contribution of each lifecycle stage to the environmental impact using the ReCiPe H/A method for the reference year 2016. The PV panel assembly has the largest contribution (**30%**), which is mainly due to the material usage of Aluminium (14%), solar glass (6%) and Copper (3%). Although the Silicon usage has significantly decreased, the contribution of SoG-Si production remains **29%** and is mostly attributed to the electricity usage (25%). The electricity consumption (10%) and Silver usage (3%) are the main hotspots for the solar cell production (**18%**). For the wafer cutting (**13%**), the impact is mostly due to the electricity consumption (4%), steel wire used for cutting (3%) and abrasive cutting slurry (2%). The contribution of the Silicon casting (**8%**) is mostly attributed to electricity consumption (6%). Finally, it is important to note that the contribution of EoL in the current model is based on assumed waste treatment management at the time of production. It would be interesting to take the time lag between first use and final waste treatment into account in future models.

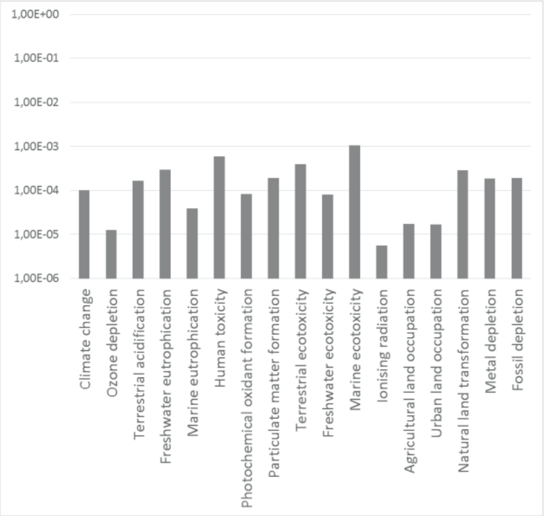

Fig. 3. Normalized potential environmental impact of PV panels using the Europe ReCiPe H/A method.

5.3. Interpretation

The results of our parametric LCA model are compared with peer-reviewed results published in academic literature that have been discussed in the previous chapter of this article. Figure 5 shows the results of our model and literature values for a time period from 2000 until 2016. The historic values, from previous LCA studies, are plotted in accordance with the year of publication because the reference year used for the LCI compilation could not always be retrieved.

Both the CED and GWP calculated historic results are comparable to previous LCA studies and they follow a similar trend. From these results it is clear that the PV industry has achieved some major improvements over the last decade in terms of environmental impact reductions. Since the improvement measures with limited investments have already been implemented, continuing to lower the environmental impact of PV energy in future will become more challenging. Nevertheless, as forecasted by industry trends reports, a further reduction in material and energy usage is expected.

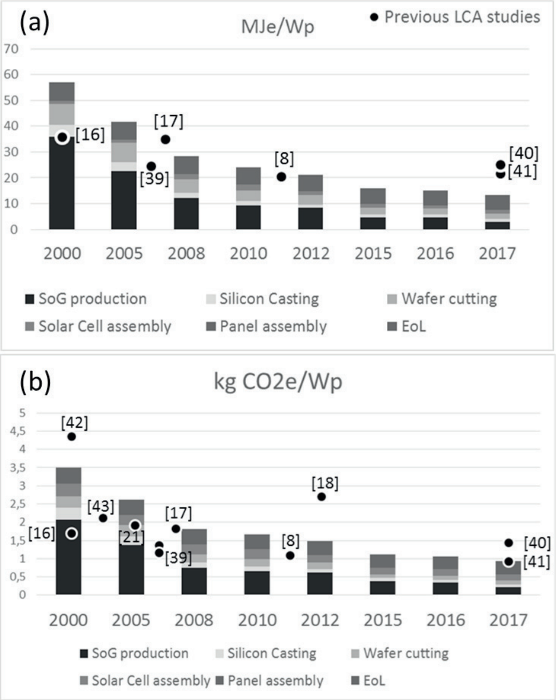

Fig. 4. (a) Historic trend of CED for mc-Si PV panels; (b) Historic trend of climate change for mc-Si PV panels.

Figure 5 shows the contribution of the different lifecycle stages to the overall environmental impact calculated as a single score with the ReCiPe H/A method for the years 2006 and 2026. It is obvious that the reduction of electricity use for the Silicon production combined with the reduced Silicon usage per Wp have a major impact on the environmental footprint of PV panels. The total impact of the Silicon wafers, represented by the SoG-Si production, Silicon casting and wafer cutting, accounted for 73% of the environmental impact of PV panels in 2006. Figure 5 shows that the contribution of the Silicon wafers in 2016 has already been reduced to 49% and based on expected trends this could further reduce to 35% by 2026. Because of these significant improvements, other lifecycle stages, such as solar cell production, PV panel production and EoL contribute to a larger part of the overall potential environmental impact. The absolute contribution of solar cell production has however decreased with 6% between 2006 and 2016 due to less required energy and reduced amount of Silver used in the metallization paste. By 2026, the main contributor of the environmental impact of the PV panel will be the last manufacturing step, the PV assembly, unless further dematerialization is achieved by using less virgin Aluminum, solar glass and copper.

By applying effective recycling technology the reuse of materials can further reduce the impact of PV panels with 6% for conventional recycling of Aluminum and with 9% if improved EoL management is implemented allowing Silver, Copper and solar glass to be recovered as well with a higher purity. Based on the current estimation, the contribution of end-of-life treatment would increase from 3% to 7%, but this would be more than compensated through the reduced impact of raw material extraction.

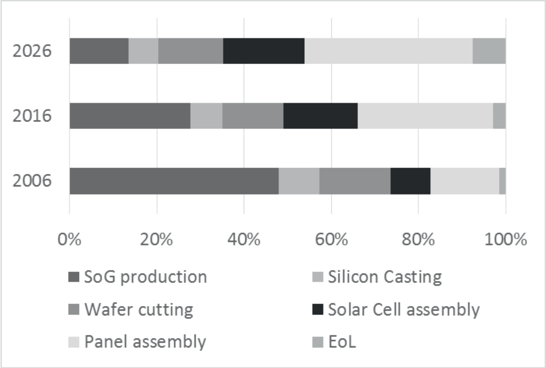

Fig. 5. Contribution to overall single score environmental impact per lifecycle stage for reference year 2006; 2016 and 2026.

6. Conclusions

This study shows that is it feasible to model historic and potential future environmental impacts based on available information related to evolution in technology, manufacturing, use and end-of-life treatment of products such as PV panels. Compared to previous LCA studies, the environmental impact of PV was often underestimated in earlier years but more recent results tend to overestimate the potential environmental impact due to the use of outdated LCI data.

The presented parametric LCA model is used to highlight past achievements along the PV supply chain between 2006 and 2016: (1) 64% reduction in terms of embedded energy [MJe/Wp], (2) 52% reduction in terms of climate change [kg CO2e/Wp] and (3) 50% reduction in terms of overall normalized environmental impact [eco-points/Wp]. Current realized improvements have been obtained in previously identified hotspots such as Silicon wafer production. Additionally the model enables us to identify potential future hotspots that will need to be addressed. Based on these results, we can conclude that it will be vital for the PV industry in the coming years to invest in proper eco-design of the PV panel to allow reuse of specific components such as the Aluminum frame and effective EoL-treatment that enables the recovery of high quality secondary materials.

Acknowledgements

The authors acknowledge support of the research fund of KU Leuven through Project GOA/15/012-SUMMA.

References

[1] IEA-PVPS. A Snapshot of Global PV (1992-2015). 2016.

[2] IEA. Technology Roadmap: Solar Photovoltaic Energy 2014 edition. 2014.

[3] Sinha P, de Wild-Scholten M, Wade A, Breyer C. "Total Cost Electricity Pricing of Photovoltaics". Presented at the 28th European Photovoltaic Solar Energy Conference, Paris; 2013.

[4] ITRPV. International Technology Roadmap for Photovoltaic (ITRPV) 2015 Results including maturity reports [Internet]. 2016.

[5] IEA-PVPS. Trends 2016 in Photovoltaic Applications Survey Report of Selected IEA Countries between 1992 and 2015. 2016.

[6] IRENA. Renewable Energy Auctions: Analysing 2016. 2017.

[7] Gerbinet S, Belboom S, Léonard A. Life Cycle Analysis (LCA) of photovoltaic panels: A review. Renew Sustain Energy Rev. 38, 747–753. 2014

[8] Sumper A, Robledo-García M, Villafáfila-Robles R, Bergas-Jané J, Andrés-Peiró J. Life-cycle assessment of a photovoltaic system in Catalonia (Spain). Renew Sustain Energy Rev. 15, 3888–3896. 2011

[9] Latunussa CEL, Ardente F, Blengini GA, Mancini L. Life Cycle Assessment of an innovative recycling process for crystalline silicon photovoltaic panels. Life Cycle Environ Ecol Impact Anal Sol Technol. 156, 101–111. 2016.

[10] Kang S, Yoo S, Lee J, Boo B, Ryu H. Experimental investigations for recycling of silicon and glass from waste photovoltaic modules. Renew Energy. 47, 152–159. 2012

[11] IRENA, IEA-PVPS. End of life management Solar Photovoltaic Panels. 2016.

[12] Fthenakis VM. End-of-life management and recycling of PV modules. Viability Sol Photovolt. 28, 1051–1058. 2000.

[13] Fraunhofer IBP. Life Cycle Assessment (LCA) screening of the Maltha recycling process for Si-PV modules – Executive Summary, 2012.

[14] ISO 14040 International Standard. Environmental Management-Life Cycle Assessment – Principles and Framework. 2006

[15] Goedkoop M, Heijungs R et al, ReCiPe A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level. ReCiPe Report, 2013

[16] Alsema E., Nieuwlaar E. Energy viability of photovoltaic systems. Viability Sol Photovolt.. 28, 999–1010. 2000.

[17] Pacca S, Sivaraman D, Keoleian GA. Parameters affecting the life cycle performance of PV technologies and systems. Energy Policy. 35, 3316–3326. 2007

[18] Desideri U, Proietti S, Zepparelli F, Sdringola P, Bini S. Life Cycle Assessment of a ground-mounted 1778 kWp photovoltaic plant and comparison with traditional energy production systems. Energy Solut Sustain World - Proc Third Int Conf Appl Energy. 2012.

[19] Stoppato A. Life cycle assessment of photovoltaic electricity generation. 19th Int Conf Effic Cost Optim Simul Environ Impact of Energy Syst. 2008.

[20] M.J. de Wild-Scholten (2014) Life Cycle Assessment of Photovoltaics Status 2011, Part 1 Data Collection, report published by SmartGreenScans, the Netherlands

[21] Jungbluth N, Bauer C, Dones R, Frischknecht R. Life Cycle Assessment for Emerging Technologies: Case Studies for Photovoltaic and Wind Power (11 pp). Int J Life Cycle Assess. 10, 24–34. 2005.

[22] Sinke W. Wafer-based crystalline silicon module at 1 €/Wp: Final results from the CrystalClear integrated project. In Hamburg, Germany; 2009.

[23] Heinz Ossenbrink, Arnulf Jäger Waldau, Nigel Taylor, Irene Pinedo Pascua, Sandor Szabó. Perspectives on future large-scale manufacturing of PV in Europe. Ispra Italy: Joint Research Centre; 2015.

[24] Fraunhofer Institute for Solar Energy Systems, Dr. Simon Philipps, Werner Warmuth. Photovoltaics Report. [Internet]. 2017

[25] Biyik E, Araz M, Hepbasli A, Shahrestani M, Yao R, Shao L, et al. A key review of building integrated photovoltaic (BIPV) systems. Eng Sci Technol Int J. 20, 833–858. 2017.

[26] Elkem. "Technology and Innovation of Silicon Based Processes and Products: Elkem Solar Silicon." Accessed July 15, 2017.

[27] Frischknecht et al "Life Cycle Inventories and Life Cycle Assessment of Photovoltaic Systems, International Energy Agency (IEA) PVPS Task 12." Report IEA-PVPS. 2015.

[28] Nasch, Philippe, and Romain Sumi. "Meeting Current and Future Wafering Challenges." Solid State Technology 32. March 2009.

[29] 1366 Technologies. "Introducing a New Standard in Wafer Manufacturing." Accessed August 20, 2017.

[30] Serra, J.M., J. Maia Alves, and A.M. Vallera. "Progress and Challenges for Cost Effective Kerfless Silicon Crystal Growth for PV Application." Journal of Crystal Growth. 468, 590–594. 2017.

[31] Mojrová, Barbora. "Investigation of Contact Formation during Silicon Solar Cell Production." Journal of Electrical Engineering. 67. 2016

[32] Peeters, Jef R., Diego Altamirano, Wim Dewulf, and Joost R. Duflou. "Forecasting the Composition of Emerging Waste Streams with Sensitivity Analysis: A Case Study for Photovoltaic (PV) Panels in Flanders." Resources, Conservation and Recycling. 120, 14–26. 2017

[33] CRU International. "Prospects for Silver Demand in Ethylene Oxide and Photovoltaics - A Report Prepared for The Silver Institute." 2016

[34] IEA-PVPS. "Trends in Photovoltaic Applications." 2017.

[35] Cesaro, A., Marra, A., Belgiorno, V., Guida, M.. Effectiveness of WEEE mechanical treatment: Separation yields and recovered material toxicity. J. Clean. Prod. 142, 2656–2662. 2017

[36] Alsema E., de Wild-Scholten, Fthenakis. Environmental impacts of PV electricity generation - a critical comparison of energy supply options. Presented at the 21st European Photovoltaic Solar Energy Conference, In Dresden, Germany; 2006.

[37] Huang B, Zhao J, Chai J, Xue B, Zhao F, Wang X. Environmental influence assessment of China's multi-crystalline silicon (multi-Si) photovoltaic modules considering recycling process. Sol Energy. 143, 132–141. 2017

[38] Sagani A, Mihelis J, Dedoussis V. Techno-economic analysis and life-cycle environmental impacts of small-scale building-integrated PV systems in Greece. Energy Build. 139, 277–290. 2017

[39] Oliver M, Jackson T. The evolution of economic and environmental cost for crystalline silicon photovoltaics. Viability Sol Photovolt. 28, 1011–1021. 2000

[40] Ito M, Kato K, Sugihara H, Kichimi T, Song J, Kurokawa K. A preliminary study on potential for very large-scale photovoltaic power generation (VLS-PV) system in the Gobi desert from economic and environmental viewpoints. PVSEC 12 PART III. 75, 507–517. 2003

[41] Fthenakis V, Alsema E. Photovoltaics energy payback times, greenhouse gas emissions and external costs: 2004–early 2005 status. Prog Photovolt Res Appl. 14, 275–280. 2006

[42] IPCC 2014, 2013 Revised Supplementary Methods and Good Practice Guidance Arising from the Kyoto Protocol, Hiraishi, T., Krug, T., Tanabe, K., Srivastava, N., Baasansuren, J., Fukuda, M. and Troxler, T.G. (eds) Published: IPCC, Switzerland.

[43] Frischknecht R., Jungbluth N., et.al. (2003). Implementation of Life Cycle Impact Assessment Methods. Final report ecoinvent 2000, Swiss Centre for LCI. Duebendorf, CH, www.ecoinvent.ch