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Authors	Herceg, Sina;Dick, Monique;Gervais, Estelle;Weiß, Karl-Anders
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## Conceptualized Data Structure for Sustainability Assessment of Energy and Material Flows: Example of a PV Life Cycle

Sina Herceg<sup>(a)</sup>, Monique Dick<sup>(a)</sup>, Estelle Gervais<sup>(a)</sup>, Karl-Anders Weiß<sup>(a)</sup>

a) Fraunhofer Institute for Solar Energy Systems ISE, Freiburg, Germany

**Keywords:** circular economy; life cycle assessment; photovoltaics; recycling; life cycle modeling.

**Abstract:** Traditional linear value creation is showing its limits in terms of resilience and sustainability thus underlining the need for alternative business mind-sets such as circular thinking. The current unsustainable use of natural resources and their environmental impacts over the full life cycle represent one of the major challenges of the 21st century. The continuous increase in raw material extraction and processing, fueled by global population growth and increasing production and consumption patterns will lead to surpassing the planetary boundaries, resulting irreversibly in ecological, economic, and social consequences. In the future, value chains need to be transformed into sustainable value creation cycles to ensure sustainable consumption and production. Well-established sustainability assessment methods like Life Cycle Assessment (LCA) evolve towards assessing not only production but also the whole value creation cycle. However, modelling of closed loops requires a range of specifications that are often not accounted for in current LCA literature. We identified those challenges based on literature search and own findings and discuss their implications for assessing the ecological sustainability of photovoltaic (PV) value creation cycles. Overall, the lack of data on material quantity, (sub-)product quality loss and recycling processes is a key barrier in modelling circular value chains in PV. Addressing this challenge by collecting targeted information during the use and end-of-life phases while selecting adapted allocation and modelling approaches are the first steps to identify ecologically sound circularity strategies.

### Introduction

Our present consumption and production patterns continue to exceed our planetary boundaries (Rockström et al., 2009; Sala et al., 2020). Consequently, stakeholders from politics, science and industry are trying to find ways to transform traditional linear economies into sustainable and intelligent circular economies (European Commission, 2020). The scientific debate on how to measure and assess circularity is ongoing. Several studies suggest that circularity indicators like the Material Circularity Indicator (MCI) (Ellen MacArthur Foundation & Granta Design, 2015) should not be used solely, but in combination with Life Cycle Assessment (LCA) to provide a complete view on the overall sustainability of circular economy strategies (Glogic et al., 2021; Lonca et al., 2018; Niero & Kalbar, 2019; Schulte et al., 2021). LCA has increasingly been used in the last years to evaluate the environmental performance of recycling and end-of-life (EoL) processes. Still, those studies often fail to properly address the methodological challenges that arise with the assessment of circular value creation cycles

instead of linear value creation chains (Astrup et al., 2015; Laurent et al., 2014a; Laurent et al., 2014b). From a modelling point of view, the LCA methodology provides no clear guidance when assessing continuous life cycles, as envisioned in a circular economy (Niero et al., 2016). Modelling choices like allocation have to be aligned with the scope of assessing closed product loops (Astrup et al., 2015; Vadenbo et al., 2017). A study design must be chosen that reflects the quality of recycled materials as well as possible losses in material quantities. Circularity assessment is often characterized by poor data availability. For example, life cycle inventory data on recycling processes are highly under-represented in commonly used LCI databases like ecoinvent or GaBi.

A well-structured approach is essential to close the loop in life cycle assessment for complex products like photovoltaic (PV) modules. This paper aims to give an overview of the challenges encountered in closed-loop modelling for life cycle-based sustainability assessment and provides a framework on how to systematically tackle these challenges on the example of silicon PV modules.

## **Towards Circularity Assessment for PV modules: Status-quo**

Global installed capacity for solar PV modules could reach 14 TW by 2050 (IRENA, 2021). Despite the environmental benefits of an energy system transformation towards renewable energy sources, their massive deployment will cause production emissions and an increased demand for certain resources (Gervais et al., 2021). Circular economy strategies have the potential to partly compensate for the growing raw material and energy demand.

PV modules are part of the WEEE directive which administers the take-back and disposal of waste electrical and electronic equipment (WEEE, 2012/2018). Present-day PV recycling usually takes place in facilities for metal and glass recycling, recovering the bulk materials aluminum, glass and copper (state-of-the-art recycling, Figure 1a). The laminate -including cell, plastics, lead, silver and others- will be shredded and land-filled after energy recovery through incineration. More dedicated recycling is being developed on lab-scale and prototype level and is depicted in Figure 1b (highest value scenario) according to current research.

Table 1 illustrates several waste management pathways which lead to different recovery rates of recycled material. Material quantities but also resource quality can vary before and after the end-of-life treatment process. Products with a long lifetime can be more affected by mechanical and physical stress during use phase which can alter their material properties. Energy technologies are often also exposed to climatic stresses like high insolation and a corrosive atmosphere.

During their useful lifetime, PV modules suffer from performance losses due to degradation (Köntges et al., 2017). Changes in materials and product properties during the use phase can have an influence on their cyclability. Also, for other product groups, especially plastics (e.g. food packaging), contamination or losses occurring in use can affect their cyclability as well (Eriksen et al., 2019). Changes in the material properties during this phase can lead to the respective materials not being suitable for reuse in the same product segment, but to downcycling or energy recovery.

Various aspects make PV modules a good study subject for analyzing circularity. With growing PV installations worldwide, also their EoL treatment is increasingly becoming the focus of studies and regulations. PV modules have a relatively well-defined lifetime of around 30 years and a well-known material composition. Projections on future deployment exist as well as documentation on how many modules are currently installed worldwide (VDMA, 2020). Modelling and assessing PV module value creation cycles face however major data-related challenges, as listed below.

## **Key Challenges for modelling circularity in life cycle-based PV assessment**

Based on a literature search and on our own findings, we identified the key data-related challenges for modelling closed loops in life cycle-based approaches to assess the ecological sustainability of products.

### *Downcycling, material and quality loss for PV modules*

Recycled material is often assumed to replace an equal amount of virgin material, thereby neglecting that material degradation or inefficient recycling processes can cause reduced material quality which is only suitable for application in lower quality products. Further, material losses during use, waste collection or waste processing must be considered when modelling product systems for a circular economy.

At present, downcycling in PV module EoL treatment appears at least for the high-quality solar glass, which is usually shredded, processed and reused as flat glass. Aluminum and copper are sold on the market for secondary metals. In the future, silver and other precious metals will be recovered to feed the growing demand of scarce and valuable resources. Further, the recovery of silicon for reuse either in PV wafer production or in other electronic applications is anticipated (Table 1). Silicon wafer production needs high quality solar grade silicon as an input, making multiple purifying and processing steps necessary to reuse secondary silicon. Those processes are not developed to date and need to be closely monitored by LCA studies to prevent trade-off

Module section	Material	Mass composition <sup>[1]</sup>	Recovery rate <sup>[2]</sup>	Possible EoL management pathways <sup>[3]</sup>
Front glass	Glass	67,02 %	95-100 %	Recycling (glass fiber, glass wool, float, container, glass foam), landfill
Frame	Aluminium	16,16%	94-100%	Recycling (secondary aluminium)
Junction Box	Copper	0,59%	0-100%	Recycling (secondary copper)
	Plastic (HDPE)	0,18%	0-100%	Incineration (energy recovery)
Encapsulant	EVA	6,66%	0%	Incineration (energy recovery), hazardous landfill
Backsheet	PET	3,47%	0%	Incineration (energy recovery), hazardous landfill
Solar cell	Silicon	5,29%	80-95%	Recycling (metallurgical-grade silicon), landfill
	Aluminium	0,32%	0-50%	Recycling, landfill
	Copper	0,19%	79-100%	Recycling (secondary copper), landfill
	Silver	0,02%	50-94%	Recycling (secondary silver production), extraction in refinery industry
Other metals	Tin	0,10%	0-100%	Incineration, landfill
	Lead	0,01%	0-100%	Recovery, landfill

**Table 1: Possible EoL management pathways for silicon PV modules and possible recovery rate. Own calculations based on [1] Frischknecht et al. (2020). [2] Latunussa, Ardente, et al. (2016); Huang et al. (2017); Strachala et al. (2017); Jung et al. (2016); Wang et al. (2012); Latunussa, Mancini, et al. (2016). [3] see Latunussa, Ardente, et al. (2016); Tsanakas et al. (2020); International Energy Agency Photovoltaic Power Systems Programme (2017); Strachala et al. (2017).**

between processing emissions and recycling benefits. The recycling of the polymer fraction, namely PV backsheet and encapsulation, is, to the author's knowledge, not a focus of current PV research, due to its low share of the modules production emissions (up to 2 % for the backsheet (Herceg et al., 2021) in combination with its low economic value.

Material loss due to incorrect handling during waste transport and sorting can result in glass fracture or breakage of the laminate, which can make it difficult or impossible to separate the product components at the recycling facility (UBA, 2020).

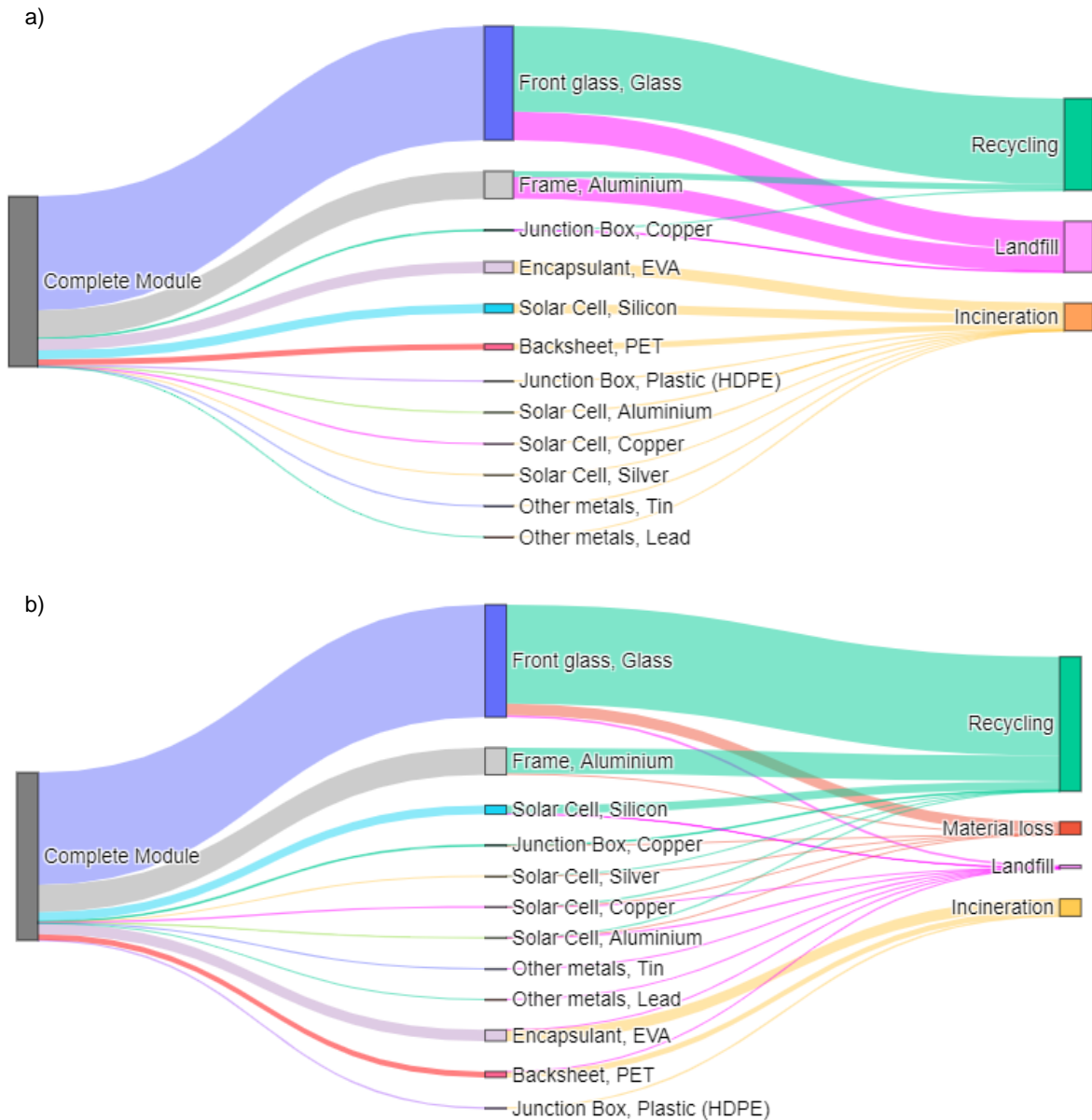
#### *Product and material composition*

In most cases, waste is received at a waste treatment facility without further information on its origin or its composition. Sorting and cleaning are done manually or by sorting machines and robots in different procedures according to visual appearance or certain material properties like weight or magnetism. Still, many materials cannot be identified and end up in incineration or landfill.

Different PV technologies from various manufacturers are on the market. For example, the EoL treatment of thin-film modules varies from the recycling of silicon PV modules. Overall, module size and bulk material composition is relatively well-known within one technology. Still, additional components such as insulation materials can be contained within the module which pose a challenge to recyclers. New developments in PV technologies like perovskite or organic solar cells bring more uncertainty into the prediction of PV waste configuration. The exact material composition is especially hard to address for materials with a lower share in mass fraction like plastic components and metals like tin, lead or silver. Their composition might vary widely and currently does not have to be reported by the manufacturer.

#### *Allocation and modelling choices*

Allocation in life cycled based modelling is always necessary when a product system produces multiple outputs. For EoL treatment, this can include disposal, energy recovery or



**Figure 1: Waste management pathways of a PV module state. Material flows for a) state-of-the-art recycling and b) a highest value scenario.**

the production of secondary material, which are all outputs with a certain market value and can therefore be considered as co-products. In the case of EoL treatment, environmental burdens and benefits do not only have to be split between different products but also between different life cycles.

Three approaches have been defined to address allocation in EoL modelling (Frischknecht, 2010; Koffler & Florin, 2013; Werner & Richter, 2000). The *recycled-content* or *cut-off approach* draws the system boundary at the point of waste generation, crediting no

recycling benefits to the product system under study but providing secondary material as an input burden-free. The *avoided-burden* or *end-of-life approach* is crediting the product system with recycling benefits but attributing the burdens of recycling to the subsequent life cycle to the amount that it will utilize secondary material. A third approach is trying to systematically address the issue of downcycling. The so-called *value-corrected substitution (VCS)* gives partial credit of primary burdens based on an economic correction factor that reflects the price ratio of secondary

vs. primary material. This approach has originally been suggested for metal-based products. For a complex product as a PV module, time-consuming research on all components would have to be conducted.

There is no common agreement on how to treat allocation in the EoL modelling for PV modules. (Wambach, 2017) provide two LCI data sets for PV EoL treatment, one for cut-off and one for end-of-life, whereas the cut-off approach is recommended to be used to complement existing PV LCI data. In general, this decision should be based on the specific goal of the study. Still, in some cases it can be useful to come to consensus about this allocation decision, for example in the face of upcoming political regulations like the current inclusion of PV modules in the work program for Eco-Design by the European Commission (European Commission, 2016). For example, the metal industry which is one of the industries with the highest recycling rates worldwide, has decided upon using the EoL approach in LCA on life cycles of metals (Atherton, 2007).

#### Life Cycle Inventory (LCI)

While EoL treatment is becoming more important in politics, economics and research, this development is not reflected in publicly available LCI data for most technologies. For example, theecoinvent database (Wernet et al., 2016), which is among the most used by LCA practitioners, does not offer one process

for plastic recycling, while certain processes of waste plastic recycling have been well-established for several years.

However, more and more individual LCIs are published, like the *Life Cycle Inventories for the production of recycled plastics from waste electrical and electronic equipment (WEEE)* (Ecosystem, 2021). Also, for PV modules there have been strong efforts to increase data availability for the end-of-life treatment (Wambach, 2017), which make it possible to compare different waste management pathways (Herceg et.al, 2020). Also, for other PV system components like inverter and mounting structure, there are increasing efforts to close this data gap (Stamford & Azapagic, 2018).

#### Existing structures on the waste market

Especially developed countries like Germany claim that they utilize up to 81 % of their waste (Destatis, 2020). Amongst recycling, this can also mean energy recovery or composting of materials. For some materials, there is a vital export market, for example for shipping plastic wastes from European to Asian countries. While those waste utilization strategies are often not beneficial for or even harming the environment, they can have a significant economic value. This consideration should be taken into account for allocation decisions when designing a life cycle-based study to model a



**Figure 2: End-of-Life mass of PV modules depending on expected service life time (in million tons). Calculations based on waste projections from (IRENA, 2021).**

closed loop product system. According to the international *Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal* (1989), e-waste may not be exported to countries that do not have adequate recycling infrastructure. Still, illegal export is happening, thereby relocating the waste problem to other geographic locations (Deutsche Umwelthilfe, 2018).

For PV modules, there is not yet a viable recycling industry due to the currently small amount of PV waste flow. Still, considerations that might address the use of scarce or precious resources will be affected by economic decisions, thus economic considerations will influence waste treatment pathways.

#### *Product Lifetime*

A constant and substantial waste flow is crucial in making recycling profitable and recycling facilities more effective. This might collide with other circular economy goals as to increase product lifetime and to hold resources in the product cycle for as long as possible.

PV modules have a very long product lifetime of around 30 years. The amount of module waste is increasing steadily (Figure 2). Circular economy strategies do not only focus on efficient recycling strategies, but also on extending product lifetimes by repair and second-use strategies. More insight is needed on optimal product lifetime from an ecological point of view, not only for energy using but also for energy producing products. Since no information can be found on this regard, decisions rely almost exclusively on economic reasons. Centralized and specialized waste treatment facilities might be a better solution over decentral solutions on a national level. However, environmental trade-offs due to transportation over large distances should be considered (Heath et al., 2020).

#### *Multiple recycling loops*

Circular Economy aims to keep products, components and materials at their highest utility and value in a closed loop. However, some materials cannot be recycled infinitely, and each recycling loop results in quality degradation. This should be addressed in life cycle modelling when the goal of the study is to address a representative product. This can be done by integrating and averaging the LCI of the waste treatment process according to the different amounts of secondary goods recycled at different frequencies to obtain a

representative LCI (European Commission, 2012).

Further, the reuse of materials, especially in blends and alloys, bears the risk of an accumulation of polluting or even hazardous substances. For PV modules, this might particularly be the case for dopants in the silicon fraction or for non-declarable substances like additives in polymer fractions. Two of the more harmful substances widely used in PV modules with the risk of potential accumulation through multiple recycling loops are antimony in the solar glass as well as fluor which is used in PV backsheets. Since to date, no information can be found that allow the evaluation of such impacts in life cycle-based modelling, different concentrations of potentially harmful substances should be considered in a sensitivity analysis to detect possible trade-offs of recycling strategies.

## **Conclusions**

The lack of data on exact material quantities, reduced material quality and recycling processes is a central obstacle when modeling circular value chains in PV technology. Overcoming this challenge through targeted collection of information during the use and end-of-life phase while simultaneously selecting appropriate allocation and modeling approaches are the first steps in identifying ecologically sensible circular economy strategies. The requirements of information conceptualized here represent the key challenges for modelling circularity in life-cycle based PV assessment on the one hand but also provide potential solutions for a data management structure on the other.

Until this data gap is closed, sensitivity analyses or in the case of future projections, scenario-based modelling should be applied. However, all these aspects should be carefully considered in defining the goal & scope of an LCA study, even when data availability will finally be improved.

To transform linear supply chains into sustainable value creation cycles, digital technologies can be applied to trace a products life cycle from cradle-to-cradle. For example, the use of block chain technology which stores information of the modules every life cycle stage should be used as intelligent material tracing system and provides information on material composition to the recycler as easily as

by scanning an QR- or Barcode attached to the module (TAB, 2020). Digitally stored, anonymized product information could further be fed into LCI databases for scientists and certifiers to provide up-to-date environmental recommendation based on industry data and for recyclers to make informed decisions on best treatment approaches.

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