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Cradle-to-cradle approach in the life cycle of silicon solar photovoltaic panels

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ABSTRACT

The penetration rates of solar photovoltaic (PV) technology have growth exponentially and are expected to continue growing. Consequently, in the medium term, the volume of PV panels to be decommissioned will also increase, thus creating a massive amount of waste with resulting negative environmental implications.

Among the methodologies that tackle the challenges for reducing the use of non-renewable abiotic resources and the level of waste, the novel cradle-to-cradle (C2C) manufacturing approach states that we can maintain our current levels of economic growth without damaging the environment and promoting a shift in the concept of re-cycling.

While the possibility of applying C2C principles within a closed-loop material cycle (CLMC) looks promising, it still requires further research and improvement, particularly to support robust business decisions and policy development. This paper first presents the main challenges and opportunities for C2C implementation for silicon-based solar PV modules, given the complexity of creating and maintaining a true CLMC system. It then calls for urgent development of a credible scientific framework for system modelling, based on thermodynamics and mathematics, in order to truly move from re-cycling to up-cycling. As an initial step, a conceptual model and a suitable time-space scale for the required C2C-CLMC system is proposed.

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1. Introduction

Today, global installed capacity for solar photovoltaic (PV) modules has reached an estimated power of 222 GW, and it is expected to reach the 4500 GW threshold by 2050 (IRENA, 2016). Despite the environmental benefits of generating electricity from this technology, however, the linear cradle-to-grave (C2G) life-cycle of crystalline PV panels depletes non-renewable abiotic resources (NRARs), such as steel, aluminium, copper and silver, while producing toxic chemical pollution and substantial waste at the end of a panel's operational life-cycle. The amount of waste from the solar PV sector (Fig. 1) is expected to reach between 1.7 and 8 Mt in 2030 and between 60 and 78 Mt in 2050(IRENA, 2016).

One of the main drivers for these photovoltaic figures is the global population growth and its corresponding energy demand. From only 10^9 individuals by the early 1800s (Hillyard, 2011), the total human population has grown in the last three centuries to over 7×10^9 and is projected to reach nearly 10×10^9 by 2050 (United Nations, Department of Economic and Social Affairs, 2015). This accelerating population growth increases demand for energy and strains resources. Meanwhile, with most countries around the world striving to implement strategies to mitigate climate change, PV technologies are being vigorously promoted to meet targets of renewables in the energy matrix. As the global policy framework evolves further, module installation and the resulting waste generation could grow even faster than current forecasts suggest.

To date, the PV panels installed were designed with a roughly 25–30 year life cycle in mind, but without much forethought about their eventual decommissioning. Nonetheless, there is growing concern about panel disposal and the associated environmental impact (Fthenakis, 2000). In recent decades, different methodologies have emerged with a view to reducing or eliminating waste from human social and economic endeavours (e.g. the Natural Step, Bio-mimicry, Getting to Zero Waste, Resilience Engineering, Ecological Design, Green Chemistry and Self-Assembly, among

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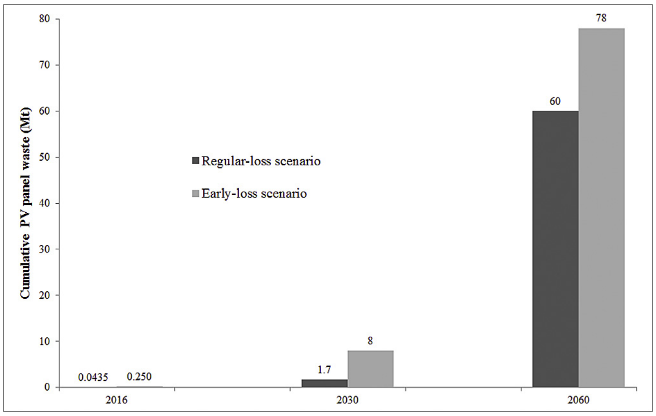

Fig. 1. Estimated cumulative global waste volumes of end-of-life PV modules.

others), promoting efficient use of abiotic resources (García-Serna et al., 2007). In this whirlwind of new concepts and methodologies, one that has captured particular attention is the cradle-to-cradle (C2C) approach, which asserts that economic growth can be achieved sustainably by designing and manufacturing products in a clean industrial ecosystem and using them within a closed loop that ultimately returns them to their source (McDonough and Braungart, 2002). It is important to mention that the C2C approach is an advanced methodology that goes beyond the concepts gathered under the definition of re-cycling, therefore, it means an innovation in the PV technology sector.

Regular-loss Scenario assumes a 30-year lifetime for solar panels, with no early attrition, while *Early-loss Scenario* takes account of “infant”, “mid-life” and “wear-out” failures before the 30-year lifespan. Source: Adapted from IRENA (2016).

Solar PV module waste offers a rich source of energy and materials that can be re-used and converted into new PV panels, electronic devices and other products. Re-cycling of PV modules is limited for the moment, partly due to the modest volume of waste available (IRENA, 2016). Panels that end up in the waste stream are classed as e-waste (Latunussa et al., 2016). However, e-waste legislation has given little consideration to treatment and re-cycling of e-waste, amid generally low awareness of the issue among policy makers and the public. It was just recently that the most relevant policy adopted to date falls under the European Union (EU) directive on Waste Electrical and Electronic Equipment (WEEE). Disposal and re-cycling of PV modules are strictly regulated by the amended WEEE directive of 2012, which required EU member states to adopt such measures in national law by February 2014. However, up-today this process is still under implementation in some member states. The transitional period for this regulation ends on 14 August 2018 (European Parliament and Council of the European Union, 2012). China, India, the United States and the rest of the world still currently have no comprehensive regulatory framework that deals with this issue.

The amended WEEE directive has encouraged the development of solar PV re-cycling facilities in the EU. Even so, varying interpretations of the directive among member states has proved challenging, whether in establishing facilities or in determining the processes and requirements for the exchange of recycled materials among EU countries. Some EU countries have succeeded in introducing and implementing clear standards and procedures for PV waste treatment and re-cycling.

However, regardless of the EU's innovative e-waste policy framework, waste generation continues largely as usual, leaving vast amounts of energy and resources destined for the landfill. In this paper, we firstly explore the challenges of PV module disposal, along with discussing opportunities for a paradigm shift in the solar PV industry, specifically from the current C2G practice to a CLMC system based on the C2C philosophy which goes beyond and it's more complex than the mere re-cycling of PV modules.

2. Methodological approach

Scientific literature on C2C applications in a CLMC for crystalline PV panels is extremely limited. The research showcased in this paper follows an initial, qualitative approach and it is structured in two parts. The first consists of a general literature review. Given the lack of subject-specific literature, this review takes into account all possible scientific and general publications or articles relating to the C2G and C2C paradigms.

The challenges and opportunities identified in this initial review give rise, in the second part, to a series of preconditions that need to be considered if we want to move from simple re-cycling to up-cycling of crystalline PV panels. These preconditions would limit the impact of the manufacturing sector, where work must expand beyond manufacturing a specified good primarily for the sake of revenue. In order to make a recognized environmentally and socially beneficial product, the solar PV industry needs to optimize the design phase to, among others; reduce impact of module temperature over the electricity generation efficiency (Coskun et al., 2017) and carbon footprint of the PV systems (Stylos and Koroneos, 2014) with the aim to finally introduce a sustainable CLMC based on C2C principles.

2.1. *Defining cradle-to-grave and cradle-to-cradle*

2.1.1. *Cradle-to-grave (C2G)*

Cradle-to-Grave (C2G) is the prevailing paradigm in the industry sector today. C2G assumes a linear lifetime for crystalline PV modules, from the extraction of material used in manufacturing them (*cradle*) until the end of their operational life, when they are considered waste (*grave*) (Fig. 2). Only a small fraction of materials is typically recovered during the “re-cycling phase” and put through a new life cycle. The equipment was not designed with this in mind, and much of the material in a panel is neither recyclable nor reusable. Consequently, even in a “cleaner production” scenario, all materials recycled are intrinsically degraded in quality and usability, so that they eventually end up in a landfill. Overall, the C2G process can be regarded as “down-cycling”.

In order to minimize the waste and pollution from C2G manufacturing, the World Business Council for Sustainable Development (WBCSD) introduced the concept of “eco-efficiency” during the 1992 Earth Summit in Rio de Janeiro (Schott, 1993). The eco-efficiency factor has been defined as the value of goods or services provided or produced to satisfy a human need, divided by their environmental load or impact (Verfaillie and Bidwell, 2000). The main principles that guide eco-efficiency (The World Watch Institute et al., 2008) are:

- Reduction in the material intensity of goods or services,
- Reduction in the energy intensity of goods or services,
- Reduced dispersion of toxic materials, improved recyclability,
- Maximum use of renewable resources,

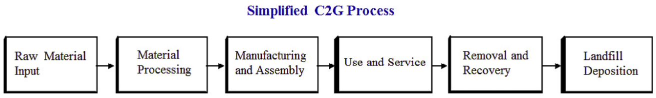

Fig. 2. Cradle-to-grave: Simplified linear flow of materials.

- Greater durability of products, and
- Increased service intensity of goods and services.

These principles resemble what is today commonly called “cleaner production”. Although valuable as an initial step, they provide only a temporary solution rather than a long-term, definitive one.

Applying eco-efficiency principles in the design of C2G products can provide a degree of environmental relief, along with certain economic benefits. However, it fails to address the need for a fundamental redesign of material flows and only inadequately addresses toxicity in current products (Braungart et al., 2007). Despite broad global acceptance, eco-efficiency has not reduced pollution, slowed the depletion of non-abiotic resources or effectively mitigated climate change. Moreover, there is no clear evidence, either historical or theoretical, that efficiency improvements will ultimately decrease the amount of resources used (Smil, 2008). Consequently, eco-efficiency is not sufficient. It can, however, be envisaged a bridge from C2G model to a new manufacturing paradigm.

2.1.2. Cradle-to-Cradle (C2C)

The cradle-to-cradle (C2C) philosophy concept was initially mentioned in the book called Cradle-to-Cradle: Remaking the Way We Make Things (McDonough and Braungart, 2002). C2C products are designed and engineered to avoid pollution to the environment, not just during their manufacture but over the whole course of their lifetime. C2C production implies a circular industrial system, where all materials are used indefinitely. PV modules' materials at the end of their life, therefore, can become in primary resource, theoretically without loss of quality, to manufacture the same or a different product, the overall process can be regarded as “upcycling” (Fig. 3).

In this constant, circular flow of materials, C2C requires two parallel cycles or metabolisms: the ***technical cycle***, whereby materials used for manufacturing a product are reused as raw materials for another new product; and the ***biological cycle***, whereby materials are absorbed by the biosphere as biological nutrients. According to C2C proponents, all materials, if adequately selected, can be re-used at the end as high-value industrial inputs via the technical cycle (McDonough and Braungart, 2002).

C2C is based on three main principles (McDonough and Braungart, 2002):

- *Waste equals food*: to fit the precise scope of this research, “waste equals resources”, which suggests that the entire *concept* of waste should be abandoned;
- *Use current solar income:* exclusively use renewable energy sources.
- *Celebrate diversity:* including in the use of materials, in order to enhance sustainability in local environmental conditions.

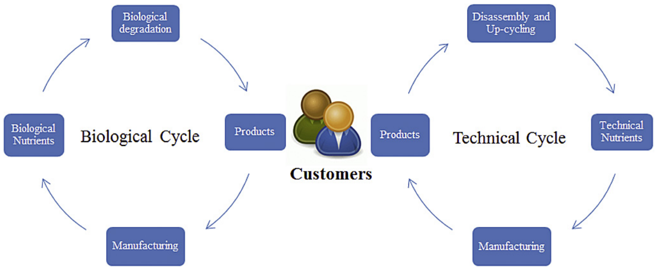

Fig. 3. Cradle-to-cradle cycles.

The only tool available today under this framework is the C2C Certification™ (MBDC LLC., 2012) and it is implemented by the Cradle-to-Cradle Products Innovation Institute (Cradle to Cradle Products Innovation Institute, 2017). This tool can be used by manufacturers to assess their goods under this framework. The certification has five categories — Basic, Bronze, Silver, Gold, or Platinum —representing the different levels of achievement under the certification scheme.

3. Theoretical approach. Closing the loop for crystalline PV panels: main challenges and opportunities

The positive environmental impact of re-cycling PV modules is well recognized, in terms of reducing emissions and avoiding further depletion of precious materials (Müller et al., 2006). Crystalline PV modules penetration rates accounted for about 92% of PV panels worldwide in 2014, with that market share expected to decline by 73.3% in 2030 and 44.8% in 2050 (IRENA, 2016), therefore, silicon-based panels are sure to remain the leading PV technology worldwide for several more decades. Further discussion in this paper will focus on these silicon-based crystalline PV modules, which will account for most of the world's panel waste for the next several decades.

Previous research has considered the practicality of re-cycling at the end-of-life (EoL) for crystalline PV panels in terms of policy, cost and technologies. The PV industry has been working to develop an appropriate framework to decommission the PV modules. However, concerns remain about module disposal in landfills, particularly in terms of health and environmental impact (Latunussa et al., 2016). Along with reducing waste and toxins, panel re-cycling could open a new market, using effective technology and economically viable methods to separate the materials embedded in the PV panel (Fthenakis and Moskowitz, 1999).

Many companies have started trying to recycle crystalline PV panels. SunPower's PV panels are the first to receive silver C2C certification (SunPower, 2016). However, up to 50 percent of the total materials used in a PV panel have to be re-usable for silver classification. Since 2002, Deutsche Solar has been investigating ways to recycle panels more effectively, achieving encouraging results in re-cycling crystalline solar cells using a combination of thermal and chemical treatment (Müller et al., 2006). Yet despite all the current efforts, the panel re-cycling and silicon recovery are still in their infancy (Latunussa et al., 2016).

The shift from linear to a circular material flow for crystalline PV panels is no trivial undertaking. There are numerous technical challenges, as well as policy and regulatory hurdles, to overcome. The results that follow are divided into two main sections. This section 3 reviews the main challenges identified for C2C panel production whereas section 4 introduces and discuss a proposed model for C2C panel production and gives the possible scope for implementing it.

3.1. Designing for up-cycling

Today's inefficient C2G use of crystalline PV panels, with minimal EoL waste recovery, increases our dependence on non-renewable abiotic primary resources and entails a negative impact for the Earth system as a whole by increasing the diffusion of residues and waste into ecosystems that also affect human life (Klee and Graedel, 2004). Therefore, the crystalline solar PV industry needs a new way of doing things. The *ultimate* goal is to maximize economically sustainable NRAR recovery that not only provides high-quality materials but also allows the Earth's system to recover from the current, unsustainable human footprint. This is not yet 100 percent achievable because today's solar PV panels are not entirely designed with such purpose in mind. PV panel manufactures would have to consider, *a priori*, designs for non-energy-intensive disassembly and total recyclability of materials, replacing toxic components with non-toxic ones in order to assess the potential to implement up-cycling at a commercial scale.

Today, only a negligible amount of non-operational PV panels reaches re-cycling facilities designed to treat waste streams from the electronic industry (Latunussa et al., 2016). However, with the transition to large-scale solar PV use still just starting, the time is right to prepare for the shift from re-cycling to proper up-cycling. To begin with, this requires gathering more data and developing a proper framework based on mathematics and thermodynamics.

3.2. *Re-cycling methods for solar cells*

In recent decades, many studies have assessed the environmental impact of the solar PV panel life cycle. Some early attempts to describe the challenges ahead were initially discussed (Fthenakis, 2000). Even today, however, literature addressing the EoL issue in detail for crystalline solar PV panels remains difficult to find, particularly in terms of re-use and re-cycling methods. Furthermore, re-cycling has not been fully studied as an alternative to panel disposal. A lack of proper data and the low numbers of panels that have reached the EoL (disposal) stage so far have limited the advance of research in this field (Latunussa et al., 2016). However, with solar PV panel disposal clearly emerging as an environmental challenge, the up-cycling of crystalline panels makes social, economic and environmental sense. Moreover, it would be consistent with the pursuit of the Sustainable Development Goals (SDGs) adopted by the United Nations in 2015.

Commercially available technologies make it possible to recycle some 80–90 percent of the materials used in today's panels, not including silicon solar cells (PV CYCLE, 2016). Conditions appear suitable, therefore, to start moving towards a closed-loop material cycle (CLMC) based on C2C principles. However, recovery methods must still be put in place for silicon, silver and other precious materials. Methods have been tested to recover silicon from crystalline PV panels, mostly using chemical and thermal processes, or a combination of the two, with manual or mechanical crushing and shredding (Latunussa et al., 2016).

Researchers have summarized several of the processes now available to separate the materials of a crystalline panel for re-use and re-cycling (Latunussa et al., 2016). While a combination of processes can apparently improve recovery yields, more openly accessible data is needed. Such re-cycling and recovery is mostly at pilot scale and not yet widely available (Latunussa et al., 2016). Only Deutshe Solar and PV CYCLE appear to provide re-cycling for crystalline PV panels at the commercial scale, and their processes still result in some waste disposal (Kim and Jeong, 2016). Thus, the methodology needs further improvement to create a true closed loop.

Full recovery of materials from crystalline PV panels are remains a challenge to be solved. In the meantime, we need to re-think solar PV panel design to avoid difficulty and reduce energy consumption in the later separation of panel materials. C2C principles can help to shape future panel design. In addition, other challenges must also be addressed in panel manufacturing, including scale, logistics and the replacement of toxic materials.

3.3. *Reverse logistics*

CLMC implementation calls for strong logistical support. In this case, when we think about up-cycling and re-use, we are thinking in terms of reverse logistics as a means to recover resources for the industrial and manufacturing sector. In contrast to traditional reverse logistics or sustainable closed-loop supply chains, disposal is not an option for any materials in the CLMC system based on C2C principles.

Reverse logistics has been defined as “the process of planning, implementing, and controlling the efficient, cost effective flow of raw materials, in–process inventory, finished goods and related information from the point of consumption to the point of origin for the purpose of recapturing value or proper disposal” (Saysel et al., 2002). Reverse logistics was conceived for occasions when a product is returned before use (commercial returns), when customers return a defective product (e.g. for refurbishment, repair, etc.), or when a product has not satisfied a customer's expectations for any reason. Since reverse logistics by definition can also include “disposal”, it cannot be considered a sufficient basis for a closed-loop-system. However, the idea behind reverse logistics is essential to develop a robust CLMC for crystalline PV panels, as long as we exclude the disposal option. Moreover, C2C principles such as “re-design” and “waste = food” have the potential to improve current methods, raising reverse logistics from re-cycling towards up-cycling.

In the 1990s, reverse logistics gained attention driven by global environmental and development concerns, with a benchmark 1992 publication from the Council of Logistics Management (Stock, 1992) providing the first general definition of the process. While many authors attempted in the mid-1990s to improve this definition, the essence of the idea remained unchanged (Fleischmann et al., 1997). After 2000, multiple publications stated the need to apply reverse logistics as a closed-loop supply chain. One reason was to reduce costs, waste generation and greenhouse gas emissions, and to make better use of resources (Krikke et al., 2001). Another was to develop new business models that consider the entire product life cycle (Guide et al., 2003). Yet despite these efforts to strengthen the concept of reverse logistics, little has been done based on empirical research (Álvarez-Gil et al., 2007).

For reverse logistics to provide the foundation for a C2C-CLMC system, simultaneous forward and backward transportation of materials must be considered, without disposal as an option. In the case of crystalline PV panels, failure rates and product return timeframes are vital considerations for CLMC implementation. The potential benefits are many. Reasons cited in the existing literature include:

a) Potential for manufacturers to increase their competitive advantage and pursue increase profit margin (Meyer, 1999); and
b) Environmental benefits, as required by the regulatory framework or dictated by the trend of environmental concern (Fleischmann et al., 1997). Some authors call this Green Supply Chain Management (Srivastava, 2008).

The timeframe and numbers of product returns can be estimated in advance, given the standard operational lifespan of 25–30 years for crystalline panels. Still, every panel brand would require specific calculations and detailed data to ensure effective CLMC operation.

The main methods used for this would be statistical. However, any method would have to be carefully selected based on each panel's particular manufacturing characteristics. Some researchers have highlighted the need for further research to develop more robust prediction of forecast product returns, beyond basic probabilities (Potdar, 2009). Nevertheless, the application C2C principles in panel design ought to simply the challenge of estimating return timeframes.

3.4. Appropriate policy framework

The amount of waste from crystalline panels will continue growing in the coming years, especially in light of climate-change mitigation policies and the promotion of renewables and PV technology. Consequently, waste treatment and re-cycling in this sector could become a burden in countries that lack an adequate policy framework and the necessary infrastructure to respond to the new waste stream. This is particularly true for certain developing countries. However, C2C-CLMC systems regulated by innovative upcycling policies offer a promising way to address the resulting social and environmental challenges. As noted in Section 1, the EU countries are the only ones with a dedicated policy framework for PV waste treatment and re-cycling. However, the implications of the EU framework are still limited to those countries, with only a marginal impact on the global PV industry. Other large PV markets, such as China, India and the US, along with other countries, are expected at some point to consider similar policies, driven by economic and environmental incentives. Developing countries, would have to overcome distinct challenges before enacting a policy akin to the EU's, including insufficient data, infrastructure, internal coordination and research and development (R&D) capabilities.

To ensure maximum benefit, EoL polices for PV panels should provide indications and guidelines for C2C-CLMC management. Such policies can thereby generate value and secure long-term socio-economic benefits, including creating new industries and jobs (IRENA, 2016), along with enabling the up-cycling of NRARs and replacement of toxic substances such as lead in crystalline silicon PV panels. The amount of lead present in crystalline PV panel varies from 1.64 g to 11.4 g per panel (Bio Intelligence Service, 2011). A C2C-CLMC planning and design framework for silicon PV panels would reduce NRAR consumption and prevent toxic substances from harming human health and the environment. Treatment of PV panels at the EoL stage to allow their re-circulation would be an important step in the development of a fully sustainable, circular economy.

Policies are also needed to ensure adequate financing mechanisms for PV panel up-cycling. Economic advantages ought to encourage the PV industry to make crystalline and potentially other PV technologies more sustainable and clean. The industry, however, would need to develop a new business model. The policies, incentive and financial mechanisms required for this are an area for further research.

In the longer term, the sustainability of NRAR use and waste generation by the PV industry will depend partly technological breakthroughs; partly on innovative solutions to the challenges of energy intensity and carbon dioxide (CO_2) management; but also on understanding what drives consumption patterns. All these factors must be considered in order to introduce sustainable consumption practices, minimize resource depletion, prevent waste generation, and protect the natural environment and human livelihoods.

Appropriate policies will help to promote C2C-CLMC systems, identify market opportunities, overcome resistance to change, and raise awareness about up-cycling methods for crystalline PV panels.

3.5. C2C certification vs. Life cycle assessment

C2C has developed a certification structure, which offers the C2C Certified™ designation (MBDC LLC, 2012). The certification program, currently in its third version (V3), is administered by the Cradle-to-Cradle Products Innovation Institute as an independent, non-profit, third party responsible to award the label with the goal to keep transparency and openness of the certification process (MBDC LLC, 2012). The certification is meant to encourage companies to demonstrate their achievements in C2C manufacturing, with the wider goal of showing that C2C products are viable and cause no harm to humans or the environment. All product materials are studied at the scale of 100 parts per million to verify C2C compliance.

During the certification process, products are evaluated based on C2C principles translated into five criteria that must be fulfilled (MBDC LLC, 2012). The criteria can be described as follows:

- ***Material health***: C2C products are made with non-toxic materials. If a toxic component cannot be replaced, then it must be well encapsulated in order to be re-used at the end of the product's useful life.
- ***Material reutilization (up-cycling)***: This implies a closed-loop-cycle, where materials flow repeatedly without loss of value and quality. Recyclability of material is essential to achieve efficient rates of reutilization.
- ***Water stewardship***: Water use in industrial processes must be controlled and efficient. Avoid water pollution.
- ***Renewable Energy and Carbon management***: Maximize use of renewable energy sources and technology and promote efficient use of energy.
- ***Social fairness***: Planning and design must always consider local social and economic conditions where industrial facilities are embedded.

Minimum requirements must be met for each of the four levels of certification available: Basic, Silver, Gold and Platinum. Rather than simple approval or rejection, the certification scheme supports the development implementation plans in pursuit of continuous improvement. Under the conditions defined in V3, product certification must be renewed every two years.

C2C certification can be seen as a valuable eco-label and a useful tool to assess product impact. Other tools are also useful to evaluate product quality, as well as social and environmental sustainability. The Life Cycle Assessment (LCA) tool has a long academic and industry history and comparatively wide recognition. According to a position paper by the Dutch government's NL Agency,[1] however, the LCA tool is not suitable for assessing and communicating the beneficial qualities of C2C products (NL Agency, 2011). At the same time, C2C certification focuses on its key criteria at a fixed point in time (i.e. the present), rather than along the whole life cycle of a particular good. Moreover, the certification scheme may overemphasize the material health category, resulting in goods that only comply with the “waste equals food” principle (Toxopeus et al., 2015).

Despite some discrepancies, the LCA tool can complement the overall design process, enhancing the benefits of C2C design and manufacturing. In addition the new Life Cycle Sustainability Assessment tool can furnish quantitative data (Finkbeiner et al., 2010), allowing more definitive communications on the benefits of C2C products. In our view, the issues noted above seem to reflect limited dialogue between the different evaluating bodies rather than any critical incompatibility between C2C certification and LCA methodology.

3.6. Appropriate mathematical and thermodynamic framework

C2C-CLMC systems are a complex, multi-parameter and

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[1] NL Agency is a department of the Ministry of Economic Affairs, Agriculture and Innovation of The Netherlands that implements government policy for sustainability, innovation, and international business and Caution. It is the contact point for businesses, knowledge institutions and government bodies for information and advice on financing, networking and regulatory matters.

multidisciplinary subject of research. Despite the attraction of C2C principles, their application in a closed-loop remains a conceptual objective, lacking the mathematical and thermodynamic framework to stimulate research, understand implications and gain recognition in the academic community. Closed-Loop-Supply-Chain models used today on Solar PV industry (Kim and Jeong, 2016), meanwhile, rely mainly on mathematic-probabilistic models not considering all the dynamics implications of various time-scale regimes of the materials and products involved in a product and the thermodynamic aspects of a CLMC implementation are ignored. Yet the potential environmental and social benefits of the C2C-CLMC model would justify a critical examination, adaptation and modification of current models along with the development of dynamics models.

For a successful introduction into commercial manufacturing and global economic system, C2C has to move beyond the realm of philosophy. A rigorous scientific framework would improve our understanding of C2C-CLMC system dynamics, their implications, and the interdependence between human activities and nature. This framework must be mathematical and thermodynamic, in order to provide new foundations for further research and modelling of C2C-CLMC systems. First, however, a suitable but simple conceptual model and a time-space scale are necessary. In the next section, we briefly introduce these elements, which will be crucial to explain the flow of materials in a C2C-CLMC, whether at the local or the global level.

4. Results and discussion of the C2C-CLMC conceptual model and time-space scale

4.1. Closed loop material cycle based on C2C principles

Redesigning crystalline PV panels is an essential step to consider in the implementation of a CLMC approach for its production based on C2C principles. Every aspect of design, materials and the entire panel life-cycle would have to be carefully studied for the PV panel to become part of a closed-loop continuum. The main goal is to design a panel that eventually, at EoL, becomes a resource again, linking every process involved in the life cycle of this technology. C2C principles, translated into the C2C Certified™ designation described in subsection 3.5, must guide its overall life-cycle design complemented by the LCA tool. Based on the above the following main guidelines have been outlined:

- Based on the principles outlined in the subsection 3.5, we will look at industrial material flow like a natural process, such as a biological metabolism, where the materials used remain safe and healthy for the eco-system in different cycles, increasing overall system efficiency (Braungart et al., 2007). This should increase the recovery yield in up-cycling and re-use. Additionally, the use of the LCA tool during the design phase will provide a view of potential impacts over the complete life cycle of a PV panel, creating a virtual cycle for panel materials.
- In accordance with the C2C approach, we propose re-thinking the extraction of raw material, as well as design and manufacturing processes, for solar PV panels. Toxic materials should be replaced in panel manufacturing whenever possible, or else, encapsulated for subsequent re-use, aiming to minimize environmental pollution and the depletion of non-renewable abiotic materials.

As a result, we have defined the structure of the C2C-CLMC system for PV panel production as a *network* based on *graph theory* (Shirinivas et al., 2010). This C2C-CLMC system network can be described via a connected digraph containing a finite set of nodes (Ɲ) connected to a finite set of directed arcs (∧), where the ending node is connected via an arc with the first initial node. Each *process* is uniquely identified by a set of indices of the grid lines that intersect at a diagraph pair Ω= (Ɲ, ∧).

Fig. 4 illustrates a simplified C2C-CLMC system-network scheme for PV that could be applied as a broad framework to the production of any good. The network consists in four nodes that represent the sub-stages of this C2C-CLMC network and five edges, indicating the direction of the material flow. A C2C-CLMC conceptual network will provide an efficient alternative to monitor material streams and residues contributors at the level of discrete constituent aiming to close the loop of solar PV materials by up-cycling the materials. Further, the CLMC should be ideally powered by renewables to improve the benefits of the overall system.

The arrows show the sequence of the flow of mass through the system; $\tilde{\boldsymbol{u}}_{\boldsymbol{n}}$: represents the average velocity of the flow of materials and/or a product; E: represents the energy transfer in and out the system; M: represents the mass losses in an open cycle.

In addition, today's PV waste management methodology only focuses on the 3R principles: Reduce, Reuse and Recycle (IRENA, 2016). The 3R approach does not consider the redesign of PV panels and does not solve the problem of waste generation, because disposal is still considered a feasible option and recyclability is constrained by the materials involved (IRENA, 2016). The 3R approach fundamentally follows C2G, rather than C2C principles, because it allows the down-cycling of material used in PV panels. To achieve true sustainability in our C2C-CLMC model, we must revise the priorities of current waste management options. Major efforts must be focused on redesigning PV panels, replacing toxic materials with healthy alternatives, and incorporating social, economic and environmental benefits to achieve up-cycling with all the materials used (Braungart et al., 2007). Based on this new approach, the redesign and up-cycling take the highest priority (Fig. 5).

In this new conceptual model, product design and the selection of materials are crucial steps to facilitate later disassembly and up-cycling of product. New materials must comply with C2C principles to ease subsequent up-cycling. Furthermore, manufacturers will rely on predictability in the product life cycle. In the next section, we will introduce a suitable time-space scale to guide the process.

4.2. Time-space scale

In the study of a CLMC, the problem of integration of different time and space scales is greatly complicated by the simultaneous time and space scales dynamic interactions. To understand these implications over the life cycle of crystalline PV panels we have to distinguish the time-space aspects from manufacturing to decommissioning. The following summarize the time-space scale proposed for a CLMC:

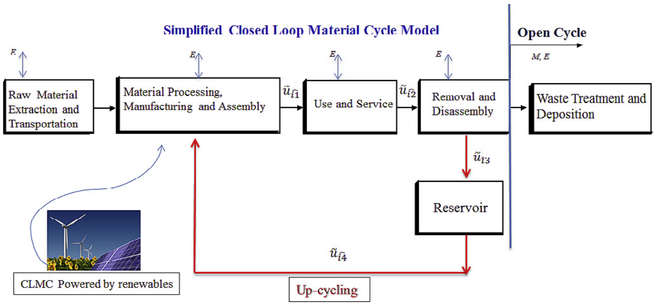

Fig. 4. The simplified closed-loop material cycle outlined in this research.

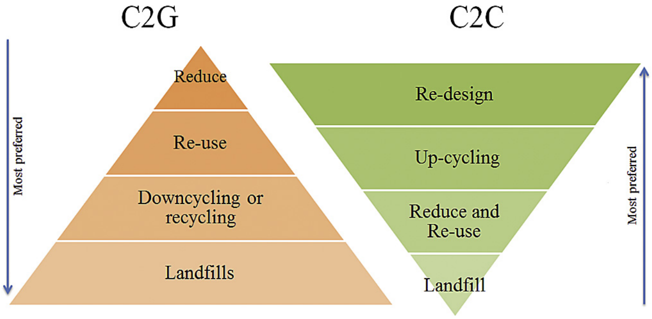

Fig. 5. Today's C2G operations versus those striving for a C2C approach.

- *Industrial phases* for crystalline PV panels (e.g. primary resource extraction, transformation of primary resources, manufacturing, transportation, storage, supply, etc.) occur in a range of horizontal dimensions (spatial scale) and over a length of time (time scale). The spatial and temporal extent of all *industrial activity* to manufacture the end product must be established to understand the impact of processes to re-use product materials in a C2C-CLMC.
- The *spatial scale* is subdivided according to the order of magnitude of the horizontal range of influence of the component products manufactured in each *industrial process*, or the distance product materials move through the process. This definition allows us to describe the horizontal range of influence of the transformation of primary resources. Since these processes depend strongly on the horizontal length scale, this scale provides a simple but effective classification system. Classifications are named based on jurisdictional and geopolitical subdivisions, as follows: Local (further subdivided into local, communal and municipal sub-categories), Provincial, National, Continental, Hemispheric, and Global. For example, a product or good manufactured with a non-abiotic primary resource extracted within a few kilometers away from the manufacturing facility and then sold and used in the same town or municipality will be considered local.
- By *time scale* we mean the “length of time” over which the imaginary volume of non-renewable abiotic primary resources composed into a product has a useful life (in this case a predicted one) in a reference frame that moves along with the product. For example, non-renewable abiotic primary resources like Al, Si, and Cu are composed to form a crystalline PV panel that has an average operational lifespan of 25–30 years. The classification schemes presented above, although only intended for reference, can help to describe the spatial and time scales of any industrial process.

Fig. 6 shows an idealized representation of spatial (horizontal length) and time scales only for some industrial products including a crystalline PV panel. Interestingly, products that moves over long distances (reflected in high space values on the graph) tend to also have a long useful life spam (high time values) as is the case for a crystalline PV panel, and vice versa. In effect, the time scale equates to the time the product takes to traverse a certain space, i.e., the distance between the manufacturing facility and final location for a PV panel. Consequently, using the time scale in combination with the space scale it is possible to estimate a rough average velocity for a particular material or product flow. Such analysis could be conducted with different levels of detail either for materials and products or both. Any constituent part of a product or material, notably, may itself have travelled over a wide range of space and time scales. The crystalline PV panels and other products illustrated in Fig. 6, for example, would consist of numerous such inputs for every materials of which the PV panel is composed.

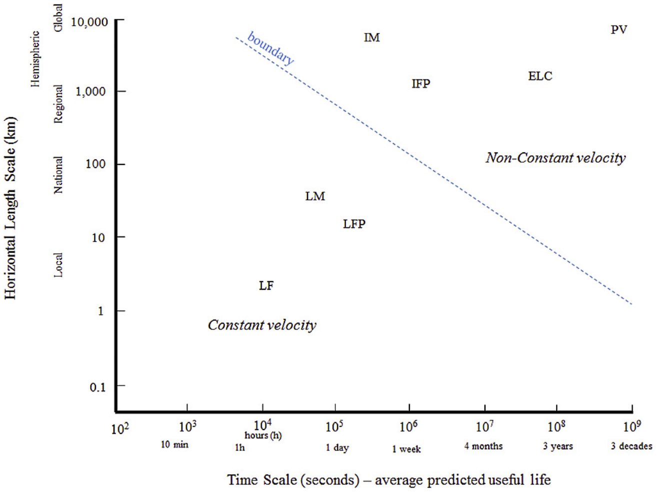

Fig. 6. Spatial and time scales for the following products: ELC: Electronic (international distribution), e.g. computers; LHC: Local household appliances; IHC: International household appliances; LM: Local media (paper-based); IM: International media (paper-based); LFP: Local food packaging; IFP: International food packaging and PV: Crystalline Photovoltaic Panels (international distribution).

Despite the general correlation between time and space values, it is possible to identify two basic types of production regimes: (1) wide-ranging, relatively long-lasting products (e.g. PV panels); and (2) local, ephemeral or disposable products (e.g. food wrappers). In the first case, where the time value exceeds the space value, velocity tends to vary at different phases of the life cycle. For example, crystalline PV panels constitute parts and materials from widely dispersed sources and may be assembled far from where they are eventually installed. Once installed, however, panels are likely to spend their whole 25–30-year operational lifespan in one place. For products with low time values (e.g. a matter of days), on the other hand, like local food packaging, the velocity of product flow can be regarded in practice as a constant. This allows us to draw an imaginary boundary between the two regimes as we can see in Fig. 6.

The application of this particular time-space scale, like the simplified representation in Fig. 6, in combination with mathematical dynamic models can help to clarify and evaluate challenges and opportunities for closed-loop system development, including for the proposed crystalline PV panel CLMC system.

Production of any good – but especially complex ones like PV panels and electronics – involves multiple time and space scales, which should be taken into account to appreciate costs and logistics at the EoL. Every material in a crystalline PV panel would have its own time-space scope, both before manufacturing and again at the EoL. While the level of complexity grows as we increase the level of detail if we include the component materials of a crystalline PV panel, models like this can provide an essential first step to grasp the making and re-making of industrial products in a CLMC.

5. Conclusion

Today's linear production and consumption pattern – based on one-way flow from extraction of primary resources to final disposal of manufactured products in a landfill – results in negative environmental impact that could severely reduce our chances of achieving a sustainable existence for human society. C2C-CLMC systems, in contrast, resemble a circle, denoting a closed-loop in which NRARs (e.g. aluminium, silicon, copper, silver, etc.) are constantly reused. Therefore, we assert that a closed-loop material cycle based on cradle-to-cradle principles (C2C-CLMC) offers an important prospect to maximize waste reduction in solar PV manufacturing, assuming that appropriate technology, proper design, and the C2C philosophy are adopted throughout the sector. In this paper, we have provided an initial overview of the challenges and opportunities to introduce a C2C-CLMC system for the production of crystalline solar PV panels. We have also introduced a conceptual model for this C2C-CLMC and the essential elements of time-space scale for industrial production flow.

Currently, there is no theoretical framework based on thermodynamics and mathematics available to support research, studies and modelling of C2C-CLMC potential, whether for crystalline PV panels or any other good or product. Since C2C-CLMC system is a cross-cutting issue, initial efforts should focus on defining a mathematical and thermodynamic framework for modelling the system, in order to investigate the actual possibilities and limitations of this novel approach. This would be useful for both industry and academia, providing far greater analytical depth than current rhetoric about the benefits of the C2C approach. Moreover, once the scientific framework and metrics are established, PV industry stakeholders will have a firmer basis for decision-making on the design of crystalline PV panels for eventual EoL disassembly.

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Acronyms

C2C: Cradle-to-Cradle
C2G: Cradle-to-Grave
CLC: Closed-Loop-Cycle
CLMC: Closed-Loop-Material-Cycle
CO_2: Carbon Dioxide
DSD: Department of Sustainable Development
ELC: Electronics

EoL: End-of life
EU: European Union
GW: Giga-Watt
IHC: International household appliances
IFP: International food packaging
IM: International media (paper-based)
IRENA: International Renewable Energy Agency
LCA: Life Cycle Assessment
LFP: Local food packaging
LHC: Local household appliances
LM: Local media (paper-based)
MBDC: McDonough Braungart Design Chemistry
Mt: Million tonnes
NRAR: Non-Renewable-Abiotic-Resources
OAS: Organization of American States
PV: Photovoltaic
R&D: research and development
SDG: Sustainable Development Goal
Si: Silicon
WBCSD: World Business Council for Sustainable Development
WEEE: Waste Electrical and Electronic Equipment Directive