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Procedia CIRP 116 (2023) 83–88

www.elsevier.com/locate/procedia

30th CIRP Life Cycle Engineering Conference.

A proposed integrated model to assess product recovery pathways: The case of solar photovoltaics

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Abstract

A Circular Economy (CE) is facilitated by the closing of material flow loops. This requires the development of complex collection, sorting, and product recovery mechanisms. Besides infrastructural challenges, product recovery is further complicated by the manufacture and consumption of increasingly complex multi-component and multi-material products whose design often limits efficient disassembly at the end of product life. The lack of information on how to treat end of use (EoU) products and the associated costs further inhibits recovery-related decision-making. Thus, the default EoU treatment is often simply landfilling and/or incineration resulting in the loss of valuable resources. In addition, resulting environmental degradation may be avoided when other product recovery strategies such as recycling, remanufacturing and direct reuse are applied. This paper proposes a system dynamics tool inspired by the materials recovery hierarchy to understand the sustainability impacts of EoU recovery. The model evaluates environmental trade-offs for alternate product recovery strategies prioritizing the recovery of EoU products, sub-assemblies, components, and materials over more destructive options of landfilling and incineration. A case study centered around EoU solar photovoltaic (PV) panels is used to validate the model.

Keywords: System Dynamics; Circular Economy; Materials recovery hierarchy; Solar photovoltaics; environmental impacts; product recovery

1. Introduction

A Circular Economy (CE) aims to address the growing concerns over environmental degradation and rapidly depleting natural resources via the closing of material flow loops [1, 2]. CE is facilitated by implementing conservative recovery approaches (reuse, remanufacture, recycle) and if necessary, incineration and/or landfill [3, 4]. Growing product complexity because of multiple sub-assemblies, components and materials makes end of use (EoU) product recovery challenging for a few reasons. Robust EoU infrastructures that efficiently facilitate the collection and sorting of EoU products is insufficient for future needs. Secondly, product disassembly, and subsequent segregation of materials into appropriate materials streams for further processing may be costly, both economically and environmentally, depending on the degree of product and material complexity. As a result, landfilling and/or incineration currently are the primary treatment methods for EoU products and sub-assemblies. The result is not just material contamination but also the loss of potentially valuable resources as other strategies with potentially better value retention such as reuse, and remanufacturing are overlooked.

The waste hierarchy, henceforth referred to as the materials recovery hierarchy (MRH), preserves the value of discarded products and materials via successive recovery strategies that maximize the triple-bottom-line benefits (environmental, economic, and social) and minimize resources ending up in

10.1016/j.procir.2023.02.015

landfills [5]. Ambiguity related to product recovery terminology continues to exist [6].

As per [5], generally the most preferable recovery strategy is reuse, followed by remanufacture, followed by recycle, and finally incineration and/ or landfill. Aligned with our findings from the literature, in the context of the proposed model, we put forward the following definitions:

Recovery: Any operation or measure undertaken after a product or material has reached its end of use. Recovery encompasses reuse, remanufacturing, recycling, and energy recovery [7, 8].

Reuse: Reuse is the process by which a product is used for the same application it was originally developed to address in subsequent lives without significant repairs [9, 10, 11, 12].

Remanufacture: Used products may be restored to their original specifications or may be upgraded to new specifications. Thus, remanufacturing allows manufacturers to upgrade the quality and functionality of the products without necessitating the manufacture of entirely new products and avoiding the disposal of used ones [7, 8, 9].

Recycle: Recycling is a process by which discarded resources (materials, components, products etc.) are segregated into material-level streams and processed to specifications that enable them to be reintroduced in the economy as industrial feedstock to support the manufacture of new products. Standards will be needed to evaluate these new material streams [10, 13, 14].

When materials are no longer suitable for recovery, energy recovery via processes such as incineration, gasification, pyrolization and anaerobic digestion can be explored. In the worst-case scenario landfilling may be inevitable. Facilitating product recovery aligned with a CE framework requires a systems perspective. Decision-making that supports product recovery, such as which processing method will optimize the overall results, involves multiple concurrent considerations because of uncertainties and the dynamics associated with complex systems. The capability to anticipate outcomes as a result of differing scenarios is necessary to understand and improve not just environmental outcomes, but also economic and social outcomes, and also to drive the social change that will be needed for optimal system-wide solutions. Exploring alternate scenarios supports the quest to drive technological innovation (e.g., product design and improved processing capabilities) and support the creation of novel business models (e.g., new secondary markets, industrial synergies, and product service models).

The key contributions of this study are:

1. To propose definitions for some EoU treatment processes to mitigate ambiguity
2. Identify and propose a method that could support the development of a secondary product marketplace
3. Demonstrate some benefits of different EoU treatment processes

The paper is organized as follows: Section 2 reviews the literature and identifies the gap this study aims to address. Section 3 presents the research methods that have been used to answer the identified research objectives. In section 4 describes the case study and discusses the validation and results. Finally, the main findings and future scope are detailed in Section 5 and conclusions in Section 6.

2. Literature review

Although tools that present static models in the context of CE and sustainability impacts exist, these overlook the temporal aspects of the system. In the case of product recovery, a static model could potentially overlook numerous important dynamic parameters, i.e., those that can undergo significant changes over time, such as material value loss, product demands, availability of feedstocks, and process-related parameters [15]. Dynamic systems are typically feedback problems. This is true for product recovery as well given the dynamic parameters that over time will yield differing outcomes which in turn will drive further actions, thus resulting in feedback loops. In this paper, we propose the development of a *System Dynamics* (SD) simulation model for product recovery.

Recently Guzzo et al. developed a SD model to examine a CE [1]. Franco explored SD in the context of product design and developing business model strategies to promote a CE [16], while Gao et al. use an integrated MFA-SD model to investigate a regional CE [4]. A few studies have explored product recovery using SD. Poles specifically explored the product remanufacturing scenario [17], Golroudbary & Zahraee evaluate recycling and waste collection mechanisms from an environmental as well as social perspective [18], and Farel et al. provide a cost and benefits analysis for EoU vehicle glazing [19]. Alamerew and Brissaud developed and analyzed a SD model for product recovery management system in the context of Waste Electrical and Electronic Equipment (WEEE) [20].

3. Materials and methods

The case study presented in this paper builds upon previous work and demonstrates the use of SD in the context of EoU pathways for used crystalline-Silicon Photovoltaics (c-Si PV) [21, 22]. The integrated SD model proposed here is based on the MRH and aims to capture the dynamic interactions between the numerous parameters associated with closing material loops for a given product. This is achieved via the following sub-tasks:

a. The development of a qualitative Causal Loop Diagram (CLD) to understand the parameters and their respective interactions within the system.
b. The development of a quantitative integrated SD model based on the CLD.
c. Model validation and scenario analyses for the case of EoU c-Si PV panels via data estimated and available in literature and modeled in SimaPro*.

3.1. Integrated System Dynamics – Life Cycle Assessment modeling methodology

SD is a computational simulation methodology for understanding the interconnectedness between various elements of a system to drive a given goal or set of goals [23]. SD models comprise stocks, flows and feedback loops within the system. SD models are developed via two tools; the qualitative Causal Loop Diagram (CLD), followed by the quantitative Stock-Flow model. The developed dynamic model facilitates scenario analyses under varying conditions (Fig 1).

A CLD is a means of conceptualizing the said complex interactions within a given system. According to Sterman (2000) a CLD "consists of variables connected by arrows denoting the causal influences among the variables. The important feedback loops are also identified in the diagram. Variables are related by causal links, shown by arrows. Link polarities describe the structure of the system. They do not describe the behavior of the variables. That is, they describe what would happen if there were a change. They do not describe what actually happens. Rather, it tells you what would happen if the variable were to change." [25].

A CLD comprises variables, arrows, and polarity. The arrows represent causal links between interacting variables in the system. The polarity of these causal links is depicted by either a '+' or '-' sign next to each arrowhead and represents a direct or inverse relationship between the linked variables. Causal relationships between variables can form feedback loops that are either reinforcing or balancing. While a CLD presents high-level information about a system, the next step in understanding a given system is developing and analyzing the system quantitatively. Based on the developed CLD (Fig 2), a stock-flow diagram was developed in AnyLogic* simulation software.

A SD stock-flow model comprises three elements: a stock or level, a flow variable, and an intermediate or auxiliary variable. A stock represents a reservoir of a given resource. Mathematically, the dynamic behavior of stocks is given by a time integral of the difference between net inflows and outflows. The flow variable adjusts the level of stock via these inflows and outflows. The intermediate variable can be functions of stocks or constants or exogenous inputs [18].
Thus,

$$Stock(t) = \int_{t_0}^{t} [Inflow(t) - Outflow(t)dt + Stock(t_0)] \quad (1)$$

Where, t_0 represents the start time, t represents the final time, $Stock(t)$ is the mass accumulated at time t within the specified time period as a consequence of input $Inflow(t)$ and loss $Outflow(t)$.

In this paper, the proposed model aims to understand the implications of different EoU treatments from an environmental perspective. Life Cycle Assessment (LCA) is a method to quantify environmental impacts. There is a growing concern regarding its static and linear nature. Moreover, LCA tends to focus on subsystem specific details and unlike SD overlooks the interaction between subsystems. Thus, combining LCA and SD could overcome the limitations as a

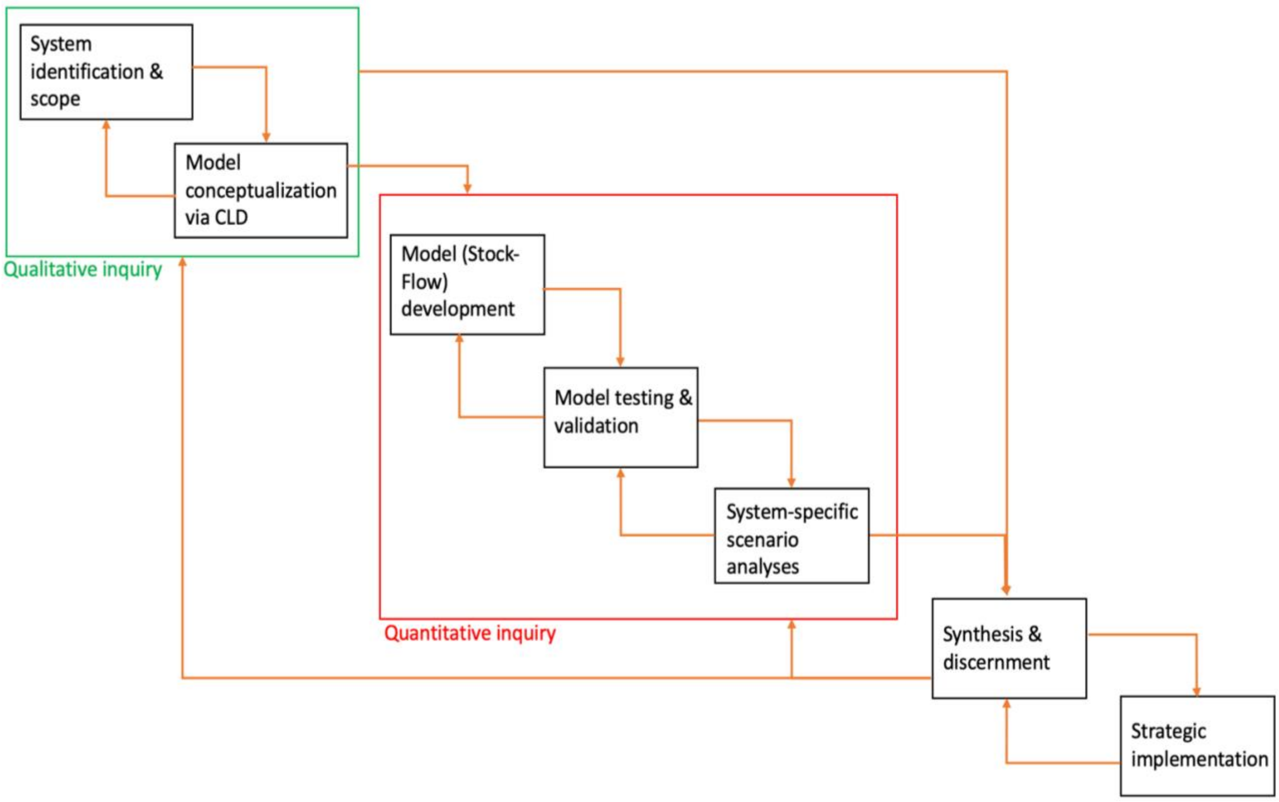

Figure 1: A schematic representation of the SD model development and application process (Adapted from [24])

*Certain commercial systems are identified in this paper. Such identification does not imply recommendation or endorsement by NIST. Nor does it imply that the products identified are necessarily the best available for the purpose.

consequence of steady-state conditions and the linear assumptions made to undertake a traditional LCA. The proposed model aims to provide a current and future understanding of product EoU quantities and the impacts of recovery under different scenarios allowing for practitioners (manufacturers, decommissioners and recyclers, and strategists and change-makers) the opportunity to anticipate, prepare and develop the means to facilitate closed loop thinking. Following the development of the model, the scenarios to be analyzed are formulated and the data is collected.

3.2. Case study and data collection

The SD-LCA model developed is used to evaluate the case of EoU c-Si PVs. The rising demand for PVs, presents a danger of EoU PVs becoming environmental liabilities if proper EoU treatment infrastructure is not developed. Owing to the increasingly complex nature of product design and the embedded value, the application of a MRH becomes increasingly important to manage resources effectively. Under the proposed hierarchy, reuse is preferable to remanufacture, which is preferable to recycling from a sustainability perspective. Building upon the study by Mathur et al. the case study here explores the dynamic nature of the EoU phase for PVs when implementing circular practices integrating the principle of the MRH [21]. The developed model quantitatively captures environmental implications under varying conditions in terms of the Global Warming Potential (GWP) index as a representative metric [26]. To evaluate the long-term GWP impacts associated with EoU PVs, this study firsts estimates the demand for PVs (in tons). The demand is computed based on the assumption that the lifetime of a c-Si PV panel is 30 years [27], that the collection rate for the EoU PVs is 100%, and that they are all the type c-Si PVs, as opposed to other PV technologies. Relative to other PV technologies, the c-SI PVs have thus far dominated the market. Therefore, initially, large amounts of EoU PVs are expected to be this type. The data used to model identified scenarios are based on data available in the literature, i.e., the EoU PV projections and environmental impacts computed via past LCA studies in SimaPro [21, 27, 28]. However, unlike past studies that focus on recycling of c-Si PVs, this study expands the analysis to include alternate EoU scenarios such as direct reuse after the warranty expires and one remanufacturing scenario as well. Since we are modeling the extreme scenarios, we assume that the recovered PV panels substitute new panels 1:1.

Table 1: Modeled scenarios

Scenario	Description
A	100% EoU c-Si PVs are landfilled
B	100% EoU c-Si PVs are reused
C	100% EoU c-Si PVs are remanufactured (glass casing is replaced due to damage)
D	100% EoU c-Si PVs are recycled

Table 1 provides an overview of the scenarios modeled. We chose these scenarios to represent some of the upper and lower bounds of environmental impacts (i.e, worst and best cases). Equations (2) through (5) mathematically represent the net impacts per ton of c-Si PVs under the identified EoU pathway scenarios (see Table 1).

In a linear economy, the c-Si photovoltaic panels are developed from virgin material feedstock, used, and ultimately disposed of in the landfill. The GWP impacts in this scenario are

$$X_{Linear,PV} = -(X_{V,PV} + X_{L,PV}) \quad (2)$$

In contrast, a 100% CE as a result of direct reuse (not considering product self-degradation and pre-processing steps, transportation, quality checks etc.) results in avoided environmental impacts and is represented as

$$X_{Avoided,Reuse} = X_{V,PV} + X_{L,PV} \quad (3)$$

Similarly, avoided impacts through remanufacturing (replacement of glass casing which is a typical failure point with the direct reuse of the remainder of the PV module) is given by

$$X_{Avoided,Reman} = X_{V,PV} - X_{V,glass} - X_{D,glass} - X_{R,glass} - X_{L,glass} \quad (4)$$

Equation 4 represents a difference between PV virgin impacts and the dismantling and recovery of broken/damaged glass, and the fact that the non-glass components of the PV were not landfilled.

Finally, avoided environmental impacts because of recycling:

$$X_{Avoided,Recycle} = X_{V,PV} + X_{L,PV} - X_{R,PV} - X_{N,PV} \quad (5)$$

where,

$X_{V,PV}$ *are impacts associated with manufacturing PVs from virgin feedstock*

$X_{V,glass}$ *are impacts associated with manufacturing the PV glass casing from virgin feedstock*

$X_{D,glass}$ *are impacts associated with dismantling the PV glass casing from an EoU PV module*

$X_{R,glass}$ *are impacts associated with recycling the recoverable PV glass casing*

$X_{L,glass}$ *are impacts associated with landfilling the contaminated PV glass*

$X_{L,PV}$ *are impacts associated with landfilling PVs*

$X_{R,PV}$ *are impacts associated with recycling EoU PVs*

$X_{N,PV}$ *are the net impacts associated with recycling EoU PVs*

Environmental impacts associated with landfilling glass and EoU PVs were modeled and obtained directly from SimaPro.

4. Results

Using the developed CLD (Fig 2), the system is subsequently modeled in the SD Software, AnyLogic. Besides the variables and links, the CLD depicts both balancing loops (B1 through B4), i.e., those interactions that tend to bring the system to equilibrium, and reinforcing loops (R1 through R6), i.e., those interactions that result in exponential growth.

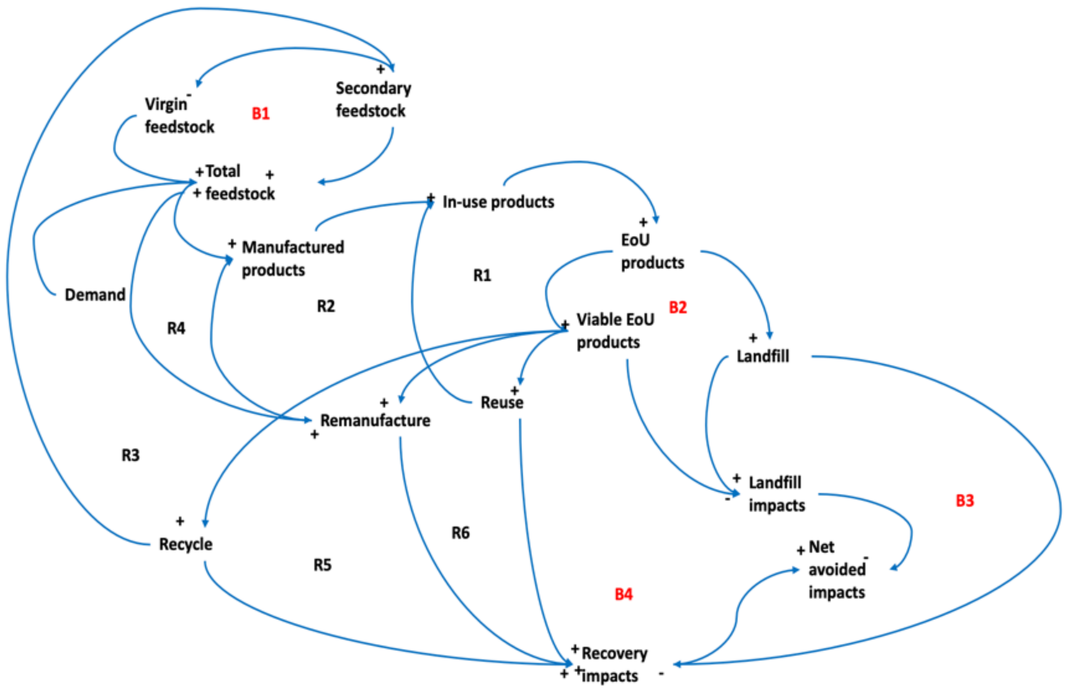

Figure 2: Causal Loop Diagram (*R1, R2, R3, R4, R5 & R6 depict reinforcing loops, while B1, B2, B3 & B4 depict balancing loops*)

The proposed SD model considers the growing demand, lifetime and resulting EoU phase for c-Si PVs. The output of the model is the net GWP (kg CO_2 eq) for the period 2016-2050 under differing EoU treatment pathways based on the notion of MRH.This simulation assumes that c-Si PVs occupy the entirety of the market share as opposed to other emerging PV technologies. Note that between 1990 and 2013 Si-type PVs occupied more than 90% of the PV market share) [29]. We computed the global PV consumption in terms of mass (late 1980s onwards – 2020) by assuming that a 1 kW generating solar panel is approximately 5.25 m^2 in reflective area and weighs 20 kg [21, 27]. Assuming a lifetime of 30 years, the mass of EoU c-Si PVs is subsequently determined from the consumption rates. Based on the consumption rates, cumulative environmental impacts (GWP) were computed under different EoU scenarios. Data pertaining to the environmental impacts is computed using values reported in previous studies [20, 30]. Additional environmental impact data was also obtained via the Ecoinvent databases in SimaPro v9.0 (Table 2).

Table 2: GWP impacts per ton under varying EoU pathways

Scenario	GWP ton CO_2 eq/ton
A. Landfill	-60.421 *(negative impact)*
B. Reuse	60.421 *(avoided impact)*
C. Remanufacture (glass casing replaced)	58.767 *(avoided impact)*
D. Recycle	57.225 *(avoided impact)*

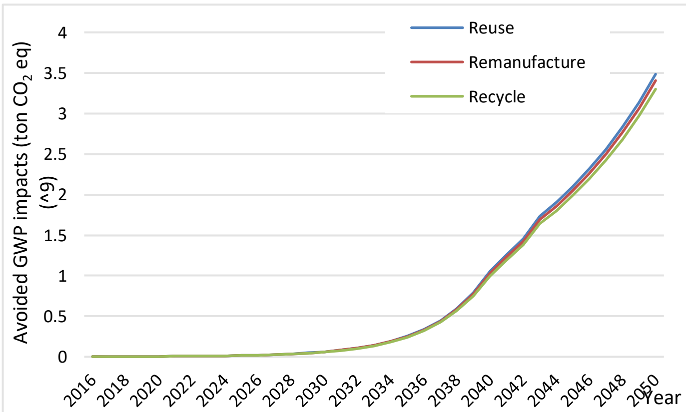

Figure 3: Cumulative avoided environmental impacts (GWP) of c-Si PVs via product recovery (recycling, remanufacturing, and direct reuse) [20, 21]

5. Discussion

The SD model presented in section 3 demonstrates the wide range of complexities related to closing the material loops to implement CE practices. The c-Si PV-specific case study presented provides an overview of the application of the waste hierarchy and the resulting impacts by modeling different EoU pathways. As expected, landfilling results in the greatest GWP impacts, while recovery of EoU PVs has the potential to significantly curb the GWP impacts over the next several years. Our results confirm that in terms of the environmental impact of recovery processes, recycling has the highest impact, remanufacturing the second highest, and direct reuse the least environmentally impactful. Interestingly, it is observed that the differences in avoided impacts between the three recovery scenarios are rather close. This indicates that impacts associated with post-use processing can be significant, particularly if the remanufacturing and recycling scenario use virgin materials. Moreover, the remanufacturing scenario considers the replacement of the glass casing. Recycling glass is a very resource-intensive process and thus also explains the higher-than-expected impacts of PV remanufacturing. Thus, EoU infrastructure that facilitates the use of recovered materials and employs innovative, low-impact post-use processing technologies need to be developed. The cases investigated via the SD model now are extreme cases. One obvious limitation of this study is that it fails to provide a realistic picture of the overall impacts associated with treating EoU PVs while considering varying collection, landfilling, recycling, remanufacturing, and reuse rates concurrently. Furthermore, the present study only considers one remanufacturing configuration (i.e., replacing the glass of the PV). Going forward other EoU recovery variations and the resulting impacts should be investigated.

6. Summary and conclusion

This paper presents the impacts of closing material loops by integrating the notion of the MRH. A CLD was developed, and translated into a SD model by integrating market specific and LCA data for the case of c-Si PVs. The model computes the environmental impact in terms of GWP under varying recovery scenarios. Going forward it should be noted that the model can be updated to capture other EoU scenarios (e.g., other remanufacturing scenarios) under varying conditions (technological, economic, and regulatory). This will support change-makers, corporate strategists and technologists developing secondary markets around EoU PVs, thus mitigating the possibility of PVs, a clean energy technology, itself from becoming an environmental liability.

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