Exploring PV Circularity by Modeling Socio-Technical Dynamics of Modules' End-of-Life Management

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Exploring PV circularity by modeling socio-technical dynamics of modules' end-of-life management

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Abstract—**The circular economy (CE) tackles environmental and resource scarcity issues by maximizing value retention in the economy. The concept implies design strategies such as reducing the use of materials or improving products' durability and end-of-life (EOL) strategies, for example, reusing products and components and recycling materials. With an estimated 80 million tons of global cumulative EOL photovoltaic (PV) modules, applying CE principles to the PV industry could alleviate resource scarcity issues while also providing economic benefits. However, transitioning to a CE may imply changes in organizations and consumer behaviors. In this context, assessment of CE strategies may require accounting for behavioral change, a requirement that methods from complex system science such as agent-based modeling meet. Thus, this paper uses an agent-based modeling (ABM) approach to study circularity in the photovoltaics supply chain. Four types of agents are represented in the ABM: PV owners, installers, recyclers, and manufacturers. Moreover, five possible EOL options – including three CE strategies – are modeled. Departing from traditional techno-economic analysis, the model includes techno-economic factors as well as social factors to model EOL management decisions. Results show that each dollar decrease in the recycling fees improves the recycling rate by roughly 1.1%. However, excluding social factors underestimates the effect that lower recycling prices have on material circularity.**

Keywords— Circular economy; agent-based modeling; socio-technical systems; circular strategies; machine learning

I. INTRODUCTION

The growing demand for solar photovoltaics (PV) raises concerns over the availability of certain minerals such as silver, tellurium, and copper [1, 2]. Currently, the linear economic model extracts resources to manufacture goods that are then discarded, causing environmental pollution and resource depletion [3]. Moreover, although minerals are essential for the economy, their increased use should not aggravate social and ecological problems [4]. The circular economy (CE) is an alternative economic model with the potential of solving those challenges [5]. The concept implies three circularity pathways (narrowing, slowing, and closing the loops), which contain nine CE strategies (refuse, rethink, reduce, reuse, repair, refurbish, remanufacture/repurpose, recycle, recover [6]).

With an estimated global 80 million tons of cumulative EOL photovoltaic (PV) modules – and 10 million tons just in the United States (US) – [7], applying CE principles to the PV industry could help alleviate environmental pollution and resource depletion issues. However, there are several challenges to improving PV circularity. First, in the US, recycling is often performed by metal or glass recyclers, which are not specialized in recycling PV modules [8]. Thus, recycling results in low material recovery rates and economic profits [9]. Due to the higher costs of recycling compared to landfill costs, recycling rates are low, with only an estimated 10% of PV modules currently recycled in the US [2]. Regarding other CE strategies, such as the reuse of PV modules or their components, other challenges arise, such as the difficulty associated with separating modules' components [2] and the limited willingness of consumers to purchase used products [10]. Given that psychological and behavioral traits often undermine the viability of technical solutions [11], individuals' and organizations' behavior ought to play a critical role in the development of second-hand markets and the adoption of recycling behaviors.

However, current studies of material circularity adopt a limited perspective, only considering the technical and economic factors favoring PV circularity [2, 12, 13]. Thus, current studies fall short in representing the achievable material efficiency potential, which is driven by consumer behaviors [14]. To overcome this limitation, we applied an agent-based modeling (ABM) approach to represent the multiple actors of the PV life cycle and the social factors (such as peer influence), constraining CE strategies to their achievable potential. The study focuses on EOL crystalline silicon (c-Si) PV modules as it is the dominant PV technology on the market.

ABM is a relevant method to study the transition to a CE transition because it adopts a systemic view, considers temporal aspects, and accounts for interactions between the system's actors [15]. The goal of this study is to explore some of the social (e.g., stakeholders' behavior change) and techno-economic conditions that can maximize PV circularity with an ABM approach.

II. AGENT-BASED MODEL OF PV CIRCULARITY

The ABM from previous work is used for this study [16]. In short, the ABM considers four of the main stakeholders of the PV industry: PV owner, installers, recyclers, and manufacturers, and five EOL options are modeled: repair, reuse, recycling, shredding, and storage. The model's objective is to explore what technical, economic, and social factors maximize PV circularity. Thus, the primary output of the ABM is the mass volumes of PV modules reaching each EOL option during the period of the simulation (set to 2020-

2050 for this study). The ABM is implemented in Python, where each agent type is a Python class defined in a Python module [17]. Thus, individual agents are instances of their classes. The model itself is contained in another Python module. During the simulations, agents interact in several ways. First, agents of the same type influence each other, thereby modeling the effect of peer influence on EOL management decisions. Second, information flows between agents of different types; for instance, installers have access to the number of PV modules handed over by PV owners for reuse. The model also contains several stochastic elements to model the variability of certain parameters (e.g., recycling costs may be different across the US).

Due to computational limitations, the number of PV owners is restricted to 1,000 (and assumed to represent the whole population), and the cumulative PV installed capacity [7] is divided among them. Product growth is modeled with the compound annual growth rate formula, using a growth rate derived from the IRENA-IEA projections [7]. The PV material efficiency growth (i.e., the increase of power capacity per unit of mass) is also derived from the same source [7]. Next, a Weibull function is used to generate the mass of EOL PV modules [7].

The theory of planned behavior (TPB) is then used to model PV owners' purchase of used or new modules and the EOL management decisions [18, 19]. The TPB accounts for three main factors affecting the intention to perform a behavior: the perceived behavioral control (PBC) (i.e., ease or difficulty of performing the behavior (assumed to only relate to financial costs)), the attitude hold toward the behavior (i.e., how the behavior is perceived as favorable or unfavorable), and the subjective norms which refer to the perceived social pressure to perform or not perform the behavior.

While the attitude is unknown and therefore calibrated, PBC is computed from the costs of each option [20, 21], and the subjective norms factor is computed as a function of the number of an agent's neighbors that have adopted a given behavior (e.g., recycling, reusing or landfilling) in the social network relating PV owners. Depending on those three factors, a score is attributed to each EOL and purchase options, and each agent selects the purchase and EOL options with the highest scores.

Installer agents sort PV modules from end-users depending on their technical characteristics (whether the module can be repaired for reuse or not). The repairability rate (amount of modules that could technically be repaired and reused) is taken from the literature [22]. Installers also balance the supply and demand of used PV modules. If there is insufficient demand for used modules or if used modules cannot be technically reused, they are sent to the cheapest EOL option available. Recycler agents compute the volume of recovered materials from EOL PV modules according to the modules' mass fraction [7] and the recycling process's material recovery rates [23, 24]. They also improve their recycling processes through the learning effect, meaning that the more EOL PV modules they recycle, the lower their recycling costs (and thus, the recycling fees) become [25]. Manufacturer agents purchase recovered materials from recyclers – at scrap prices if they exist and at virgin prices otherwise. Finally, 30 simulations spanning the 2020-2050 period (30 time-steps) are run for each scenario explored with the ABM (this number of replicates proved to be enough to capture the model's stochasticity [16]).

III. Exploring PV circularity with the ABM

Figure 1 shows the recycling rate and recyclers' net costs as a function of the recycling fees. From the figure, one can see that recycling is profitable (negative net costs for recyclers) only if the initial recycling costs are below \$21/module. Above that threshold, even when accounting for the learning effect, recycling is unprofitable. The figure also shows that from \$28/module (baseline) to \$15/module, each \$ reduction of recycling costs causes 5% more modules to be recycled. While the effect of the decreasing recycling fees on the recycling rate shrivels from \$14/module (baseline) to \$0/module, each \$ reduction of the recycling costs causing only 0.9% more modules to be recycled. Overall, each dollar decrease in the recycling fees improves the recycling rate by roughly 1.1%.

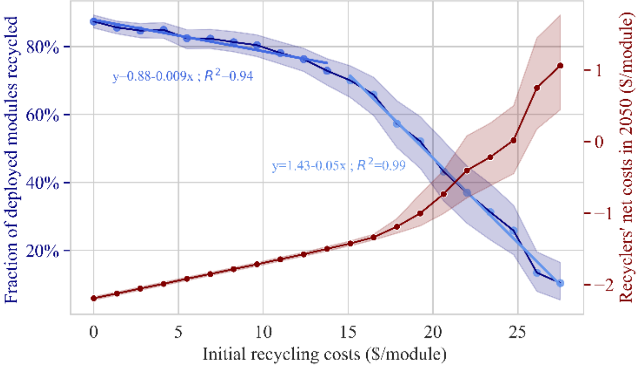

Fig. 1. Recycling rate (fraction of deployed PV modules recycled in 2050) and recyclers' net costs as a function of the recycling fees (initial recycling costs in 2020)

The plateau in Figure 1 is due to several factors: i) manufacturing waste (i.e., Silicon kerf) is always assumed to be landfilled in the model, ii) for some PV owners, storage costs (drawn from a probability distribution) are null, so storage competes with free recycling, and iii) some cliques of agents reinforce each other's non-recycling behaviors through peer influence. Moreover, the learning effect supports recycling behaviors by lowering costs further, once a few PV owner agents have started to adopt recycling behaviors, which, in turn, leads to more PV owners choosing the recycling option. Overall, if the stream of EOL modules reaching recyclers keeps increasing (which is likely in the future), the learning effect could spur profitable recycling. The simulations show that, due to the learning effect, a yearly recycled volume of EOL modules above 15,000 metric tons is enough to make recycling profitable. This threshold value is similar to the literature [13].

In our simulations, a 20% recycling target can be reached 6 years earlier with a higher subsidy (\$18/module) than with a lower one (\$10/module), limiting the period over which the subsidy is provided (it is assumed that once the target is reached, the subsidy stops). A higher subsidy to encourage recycling and exploit the learning effect is, therefore, a relevant strategy. However, as it depends strongly on the learning effect, the subsidy program should establish performance targets that verify the continuous improvement of recycling processes and, thus, ensure that the recycling costs do not return to original levels once the subsidy stops.

Finally, when costs alone are included in the TPB model (rather than the TPB's original three variables, i.e., costs, attitude, and peer influence), the recycling rate is always zero as long as recycling is more expensive than landfilling (i.e., when initial recycling costs are above \$3/module). This result testifies to the relevance of including social aspects in the techno-economic analysis because they may explain how and why a technology or behavior is adopted. In our study, the positive effect of the attitude and peer influence on circularity when initial recycling costs are high demonstrates the potential significance of nurturing early adopters of recycling behaviors as they create a trend for other PV owners to follow, which, in turn, enhance the recycling rate.

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