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D1.4

Scenario and policy analysis and development of an online tool

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3. INTRODUCTION

This deliverable is a follow-up of deliverable 1.3 (D1.3) where the details of the simulation model for Germany were presented. The purpose of this deliverable is to offer a policy and scenario experimentation tool for use by non-experts. The deliverable introduces the topic of management flight simulators to access complex differential equation models for people without specific technical knowledge. Thereby, the results from deliverable D1.3. become available to additional target groups and industries as well as the public. In the next section you find a brief description of the flight simulator designed by the modelers for users to interact with the simulation model. Section 5 then introduces scenario and policy analysis using the simulation model developed in D1.3.

4. FLIGHT SIMULATORS

Figure 1 shows a summarized representation of the development process for flight simulators. Stages 1, 2, and 3, which correspond to the stages of data gathering, model conceptualization, and formal model formulation, were already introduced in D1.3. The last step of this process is usually the development of a flight simulator. Just like pilots first learn first-hand about aviation through a simulator, management flight simulators allow users to interact with a computer simulation model in a realistic way. Flight simulators, as representations of the real world, have several advantages, namely: (i) They compress time by enabling decade-long scenarios to be tested in a matter of seconds, (ii) They allow policy makers to conduct experiments without having to fear the consequences of their decisions, (iii) They bring a live and experiential aspect to a digital object while dealing and learning about complex systems.

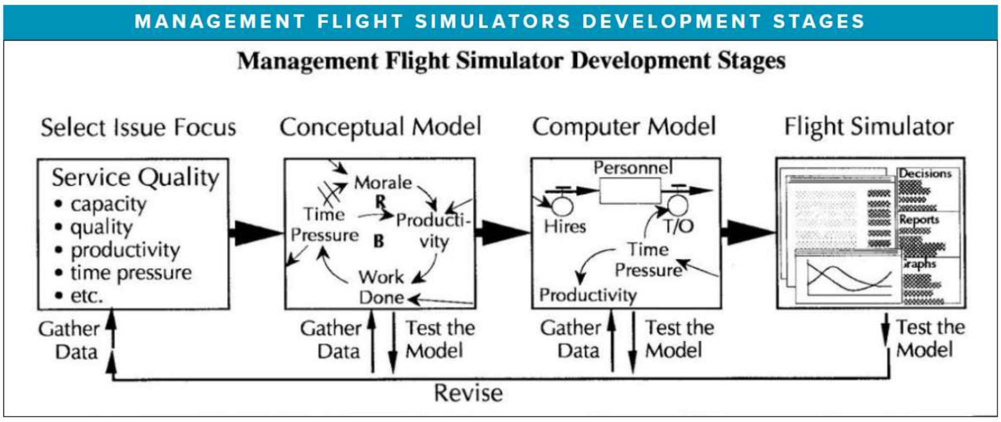

Figure 1 Management Flight Simulator Development Stages

Flight simulators display what is known as a user interface, or a set of input and output variables users can modify to test different policies and check the corresponding model outcomes. A user interface should display variables decision makers have control over, or that directly affect them. The main criteria for selection should then be that the decisions are directly relevant or easily transferable from the simulator to a real setting. Based on this premise, a description of the input and output variables used to build the model interface for the CIRCSUOL model are provided below.

4.1. HOW TO ACCESS THE MODEL AND THE MODEL INTERFACE

The system dynamics simulation model was developed with the modelling software Stella Architect from ISEE Systems (www.iseesystems.com). The model, as well as the user interface, must be accessed with a license from this software.

4.2. HOW TO USE THE MODEL INTERFACE

The model interface is intuitive to use. It consists of a home page with several options to navigate. Figure 2 corresponds to the landing or home page of the flight simulator. Here, three main options are displayed:

- About: contains information about the methodology used to build the simulation model, its main assumptions and usability notes.
- Business as usual, Scenario 1, 2 and 3: by clicking on each of these buttons, the user is taken to the different scenarios with the relevant input levers.
- Contact info: contact information in case questions arise.

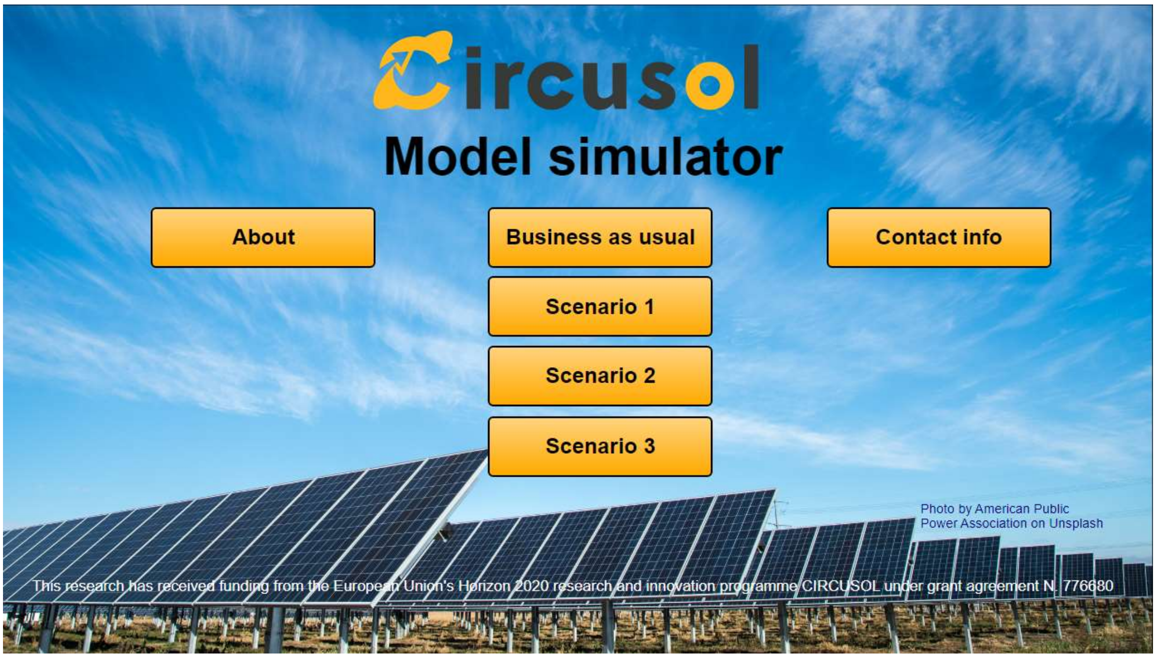

Figure 2 Simulator's welcome page

Figure 3 shows a screenshot of one of the scenario pages. It is important to differentiate between input levers and output graphs in the interface. Input levers on the left include sliders and boxes to enter numerical values. The idea here is that the user can manipulate the levers to test different scenarios or hypotheses. All scenarios contain the following general options to alter:

- Switch for early loss scenario: Switches in the model have binary values of 1 or 0. When the switch equals 1 the variable is activated or turned on, whereas when it is set to 0, it is deactivated. In the case of the proposed scenarios, the user can set the slider to 1 to simulate the model under an early loss probability of loss scenario. The details of the calculation for such probability loss are shared in D1.3.

- Minimum years to calculate supply for reuse: this corresponds to the age range that must be applied to panels that qualify for reuse.
- Alpha shape factors for early and regular loss scenarios.

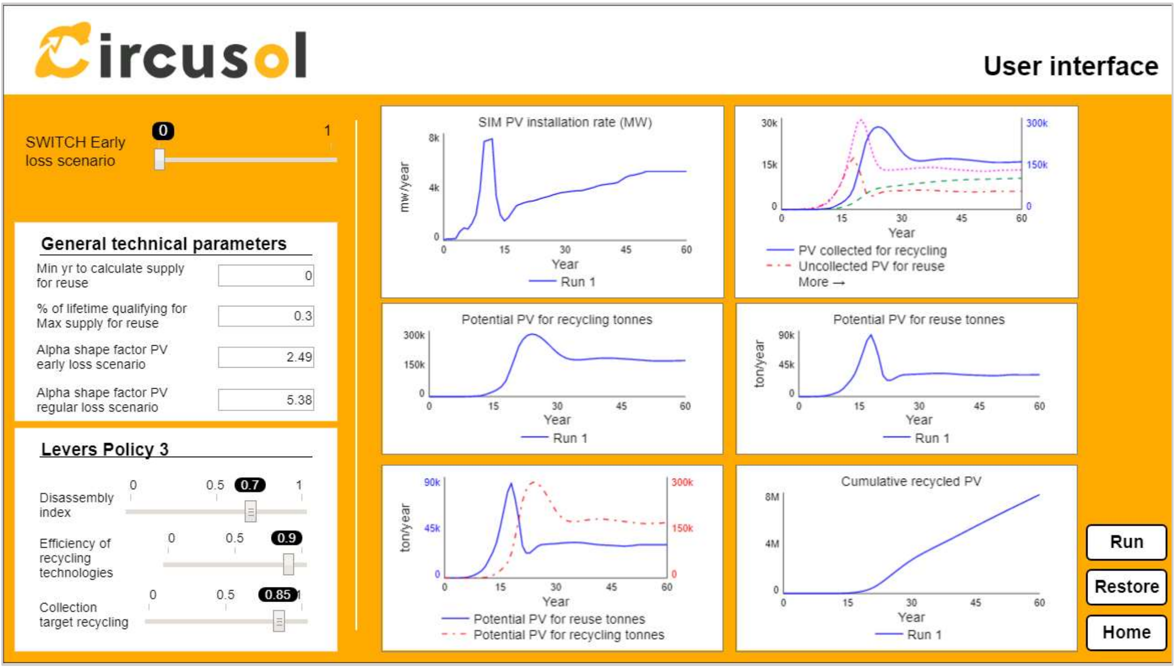

Figure 3 Screenshot of one of the pages in the flight simulator

Additionally, the three buttons in the right corner of the page correspond to:

- Run: by clicking on this button, the simulation, which is not visible, will run with the parameters specified in the left-hand side of the page. The resulting behaviour will be then displayed in the selected output variables on the right.
- Restore: by clicking on this button all the input variables will be restored, meaning set back to their original values (as used in the business-as-usual run of the model).
- Home: by clicking on this button the user will be redirected to the homepage of the simulator where the main menu is displayed.

5. POLICY AND SCENARIO ANALYSIS

The sections below present a description of the proposed scenarios and the obtained results. In conjunction with our colleagues from LUND University, the following policies and scenarios were envisioned. To create these scenarios, LUND and BUAS held a virtual meeting in MS Teams in March 2022. What appears below in quotation marks refer to verbatim text from our Lund colleagues transcribed by the BUAS team.

Table 1 Overview of the policies and scenarios developed in cooperation with colleagues from Lund University

Policy intervention	Scenario description	Other comments
Baseline	Status-quo scenario	No policy intervention to enhance circularity, business as usual.
Policy package 1 ***"Lifetime maximization of 1st life PV"***	Maximize lifetime of first life PV modules or systems	According to our colleagues at LUND University, variables that directly affect 1st life PV maximization are: • Quality "Typical legal warranties ensure coverage from 2 to 5 years for manufacturing defects. The manufacturer is responsible for the repair or to get a repair. They have more incentives to manufacture them right. If they increase the guarantee period (for example, to 10 years), there is more incentive for more quality manufacturing, lifetime of 1st life PV modules will be increased and there will be less failures." (Franco, 2019). • Training "What is lacking, is the quality of the installation, which has led to many premature defects. There could be a policy stating that only trained, certified installers can carry on installation so that defects will come down by 30% (Lars' hypothesis)" • O&M "Constant monitoring, which could allow the identification of failures at an early stage, thus reducing downtime"
Policy package 2 ***"PV reuse maximization (Europe)"***	Maximize reuse of PV modules in 2nd-life for their deployment domestically (in Europe)	According to our colleagues at LUND, policy instruments that can support PV reuse are: • "Targets for preparation for reuse for certain age cohorts" • R&D support "For repairing, logistics, and testing" • Making 2nd life PV accessible "Panels are collected by PV CYCLE (e.g., producer responsibility organization), which today with the very low volumes of discarded PV Panels can economically not

		invest in sorting the potential reusable PV Panels from the waste PV Panels and therefore all PV Panels handed over to PV CYCLE enter the waste treatment phase. There is a challenge between preparation for reuse and recycling because the sorting cost is high-cost driver. The easier the accessibility to potential reusable PV panels, more chances to prepare these for a second life. How can the accessibility be easier? Refurbishing entities could come and inspect panels themselves. The main question is: How will the collection be organized? What is the best way? Municipalities? Refurbishers? Producer responsibility organizations? How link this to waste compliance and WEEE compliance regulations in each EU-27 country?" • Green public procurement: targets This would mean, for instance, that "x% of PV installations from public organizations have to be with 2nd life PV with a clear identity card for each second-life PV Panel in order that the performance and safety of the product is guaranteed (Lars' hypothesis)" • Standardization, labelling and warranties Clear set of Reuse Criteria for PV Panels could develop second-hand markets in Europe and elsewhere.
Policy package 3 ***"Improve recycling at EOL"***	Improve conditions for recycling of PV modules at end-of-first life	Policy instruments: • **Realistic WEEE collection and recycling targets for PV Panels** Currently, European Union (EU) regulations require 65% collection target based upon the Put-on-the-Market of the previous 3 years and 85% recovery target, and 80 % shall be prepared for re-use and recycled under Category 4 where also PV Panels are part of. • **Eco-design guidelines**

		DfD or design for disassembly can be achieved through different avenues, namely: Minimizing non-reversible adhesives and bonds, Modular product construction, encapsulants with release layers or no encapsulants (Bilbao et al., 2021). For PV Panels (and inverters), the draft Ecodesign Regulation of the EU of June 2022 foresees in its Annex II, a clear set of requirements for PV Panels. • **R&D support to recycling technologies** This together with more volume of PV Panels waste can have an effect on the efficiency of recycling and disassembly. Quicker, cleaner, better recycling.
Policy package 4 ***"PV reuse maximization (outside Europe)"***	Enable responsible reuse of PV modules in 2nd-life application outside Europe (Africa / Middle East / South Asia?)	Policy instruments: • **Difficult to include in the simulation** What is to be considered a functional product for export? (i.e., the Basel convention). This is out *of the* model scope. • **Training and law enforcement** Mentioned as a factor, but not included in the simulation.

5.1. POLICY PACKAGE 1 "LIFETIME MAXIMIZATION FOR 1ST LIFE PV"

Besides the local climate and the chosen technology for the PV panel, other factors such as the bill of materials and varying manufacturing and installation quality, have been documented as critical factors influencing PV module lifetime (Kaaya et al., 2020). The section below documents the conceptualization of the factors listed on Table 1 for Policy 1.

5.1.1. SOLAR PANEL WARRANTY AND QUALITY

Solar panel manufacturers usually offer two types of warranties: (i) product warranty and (ii) performance warranty. The first category relates to material and workmanship defects or failings in the manufacturing process, environmental issues, and specific wear and tear. For instance, as stated in the warranty information sheet from the solar manufacturer Suntech: "Suntech warrants its Modules, including factory-assembled DC connectors and cables, if any, to be free from defect in materials and workmanship, as per the mechanical and electrical characteristics of the product's datasheet, under normal application, proper installation"[1]. A solar panel's performance warranty, on the other hand, typically guarantees 90% of nominal power output at 10-12 years, and 80% up to 25 years after the start of the warranty date without failing. All overall, manufacturers' product warranties ensure panel repair and replacement will take place when needed.

Table 2 Solar panel product warranty by manufacturer[2]

Solar panel manufacturer	Duration of product warranty (years)
merisolar	12
Astronergy	10
Axitec	25
BenQ Solar (AUO)	12
Boviet Solar	12
Canadian Solar	12
CentroSolar	10
CertainTeed Solar	25
China Sunergy	10
ET Solar	10
First Solar	12
GCL	10
Grape Solar	10
Green Brilliance	5
Hansol	10
Hanwha	12
Heliene	10
Hyundai	12
JA Solar	12
JinkoSolar	10
Kyocera	10
LG	25
LONGi	12
Mission Solar Energy	25
Neo Solar Power	10
Panasonic	25
Peimar	20
Peimar Group	20
Phono Solar	12
QCELLS	25
REC	25
Renogy Solar	10
Risen	12
S-Energy	12
Seraphim	10

[1] https://www.suntech-power.com/wp-content/uploads/download/Product-Warranty/2021%20Suntech%20166+%20Moudle%20Warranty.pdf
[2] Taken from https://news.energysage.com/shopping-solar-panels-pay-attention-to-solar-panels-warranty/

Silfab	25
Solaria	25
Solartech Universal	15
Suniva Inc	10
SunPower	25
SunSpark Technology	12
Talesun Energy	12
Trina	10
Upsolar	12
Vikram Solar	10
Winaico	25
Average	**15**

As seen in the table above, the average product warranty is 15 years. *Therefore, we found no justification to add product warranty* as a parameter influencing PV panels service lifetime. What we modeled instead was the combined effect of the *(i) bill of materials quality defects, and (ii) transport and installation failures as well as (iii) effectiveness of fault detection systems on the annual degradation rate of the PV panels.* The reasoning behind this formulation is that the annual degradation rate has, in turn, a direct effect on the calculated lifetime of new PV. ***Hence, <u>the higher the degradation rate, the lower the estimated PV lifetime</u>, the higher the amount of decommissioned PV (both in MW and t), and consequently, the faster the PV modules reach EOL and becomes waste.***

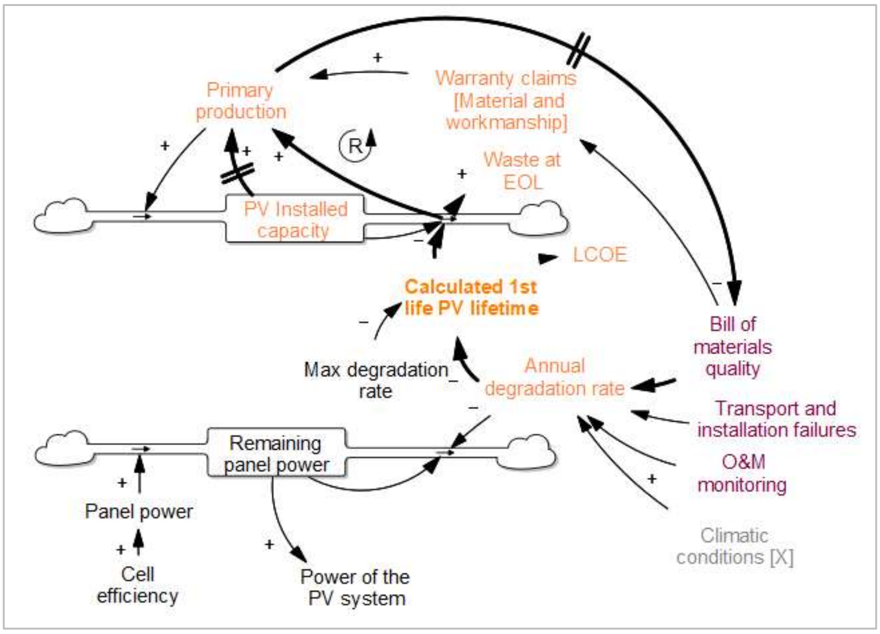

Figure 4 Schematic representation of the variables introduced in the model for Policy Package 1

The connection between degradation rates and PV lifetime predictions has been reported in the literature (see for instance Kaaya et al. (2020)). Knowing the time period PV modules and systems will last, or the remaining useful lifetime (RUL)[3] for operational systems, is of great importance for making good financial decisions[4] as well as planning operation and maintenance activities on PV systems (Kaaya et al., 2020).

COMBINED EFFECTS AFFECTING THE PV DEGRADATION RATE

Although there is **currently no standardized, and therefore no generalized, way to calculate degradation rates for PV systems[5]**, we posit, based on expert knowledge, that the PV degradation rate is affected by the *(i) bill of materials quality defects, plus (ii) transport and installation failures, as well as (iii) effectiveness of fault detection systems on the annual degradation rate of the PV panels*. Taking as an example the quality of the bill of materials factor, each of the above-mentioned effects is calculated as described next. First, a normalized value is calculated using an actual and a reference value for each of the three factors affecting the degradation rate. Normalization ensures that when the inputs X_1 equal their reference levels, the output y equals its reference level (Sterman, 2000).

$$Effect\ of\ BOM\ quality\ defects\ on\ degradation\ rate = \frac{Actual\ BOM\ quality\ defects}{Reference\ BOM\ quality\ defects} \quad \textbf{Eq. 1}$$

The assumed reference values for each of the formulated inputs are:

Variable name	Reference values
Reference BOM quality defects	0.5
Reference transport and installation failures	0.5
Reference effectiveness of fault and installation systems	0.5

Note that these reference values have been set so that when divided by the actual values, the resulting number becomes input of the final lookup table. For the three mentioned variables, the lookup tables in Stella Architect look as follows:

Effect of BOM quality defects on annual degradation	Effect of transport and installations failures on annual degradation	Effect of fault and detection systems on annual degradation

[3] The useful lifetime of a PV panel refers to its non-reversible performance loss, such that the module or system power decreases by 20% of the maximum stable power measured in the field.
[4] The LCOE of new and used PV takes PV estimated lifetime as an input parameter.
[5] As these depend rather on the model and methods used, the executing research team, the PV technology and geography-specific conditions (Kaaya et al., 2020).

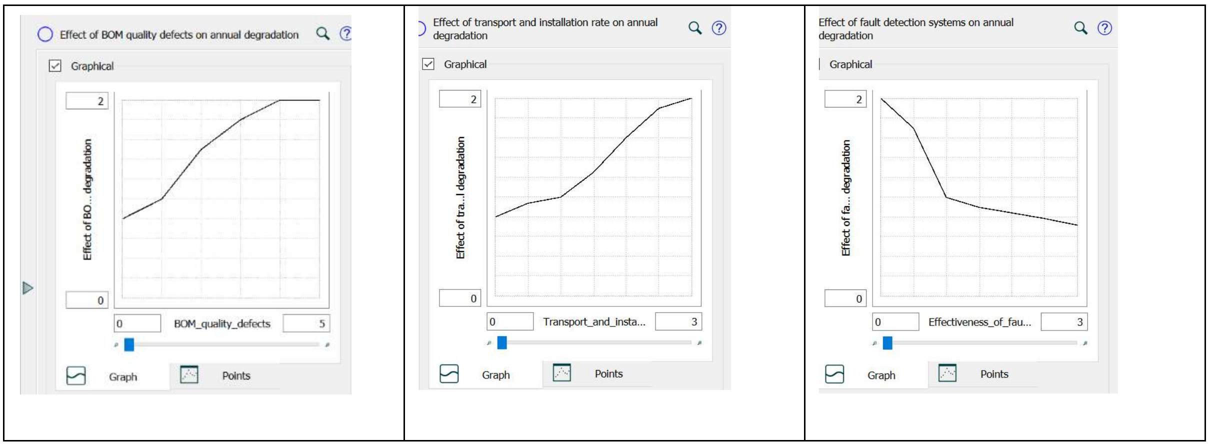

Figure 5 Lookup tables for the input variables influencing the PV annual degradation rate

The first two effects, which show a quasi s-shape behavior, indicate that when BOM quality defects and transport and installation failures increase, so will the PV annual degradation rate. On the other hand, as the effectiveness of the fault and detection system increase, the effect on the degradation rate will be minimal. Finally, to affect the "regular annual degradation rate" (see Figure 6), the conceptualized effects shown in Figure 5 are multiplied as follows:

$$\begin{aligned} &Combined\ effect\ of\ policy\ package\ 1\ factors\ on\ degradation\ rate \\ &\quad = Effect\ of\ BOM\ quality\ defects \\ &\quad * Effect\ of\ transport\ and\ installation\ failures \\ &\quad * Effect\ of\ effectiveness\ of\ fault\ and\ detection\ systems \end{aligned} \qquad \text{Eq. 2}$$

The newly calculated degradation rate affects in turn the "average 1st life PV lifetime" as conceptualized below (see also Figure 6):

$$\begin{aligned} &Calculated\ PV\ lifetime \\ &\quad = LOG10(1 - Max\_degradation\_\%\_in\_lifetime)/LOG10(1 \\ &\quad - Annual\_field\_power\_degradation\_rate) \end{aligned} \qquad \text{Eq. 3}$$

To arrive at Eq. 3, we used the traditional exponential decay[6] formula[7]:

$$F(t) = a(1 - r)^t \qquad \text{Eq. 4}$$

Where:

a	Initial value (Initial panel power)
r	Degradation rate

[6] Most degradation analyses use a linear-shaped power loss model, and therefore, assume a constant degradation rate throughout the model lifetime. However, non-linearity of power loss is usually observed in the field (Kaaya et al., 2020). Past publications (see Section 2.2. in Kaaya et al.) have reported that the power loss can be exponentially-shaped, linear-shaped, step degradation, and suturing power over time.

[7] https://www.cuemath.com/exponential-decay-formula/

t	Time

Regardless of the panel power, which varies by year, the exponential decay formula (given a degradation rate), will provide the year at which panel power reaches 80% of output (it will be the same year, regardless of the initial panel power value). This means that in this study a maximum 20% reduction in the module or system performance has been assumed. This 20% loss is arbitrary, and it has been used to make it consistent with manufacturers warranties. "In the manufacturers' context, the lifetime of a PV modules is often defined as the time required for a PV to lose its initial STC power by 20%, so that power output is not too low to be economically viable to continue operations" (IEA, 2021).

With this formula, we need to find the corresponding value for lifetime when the maximum degradation rate equals 20%. That is:

$$a(1-0.2) = a\,(0.8)$$
$$0.8a \; = a(1-r)^t$$
$$0.8 \; = \; (1-r)^t$$

Eq. 5

Solving for t:

$$t = log_{(1-r)}(1 - MD \; or \; 0.8)$$

Eq. 6

To convert the formulation above to the language in Stella[8]:
LOG10(8)/LOG10(2) equals 3 (the base 2 logarithm of 8)

The final equation is then (equivalent to Eq. 3):

$$t = log10(1-MD)/log10(1-r)$$

Eq. 7

[8] https://www.iseesystems.com/resources/help/v2/#08-Reference/07-Builtins/Mathematical_builtins.htm#LOG10

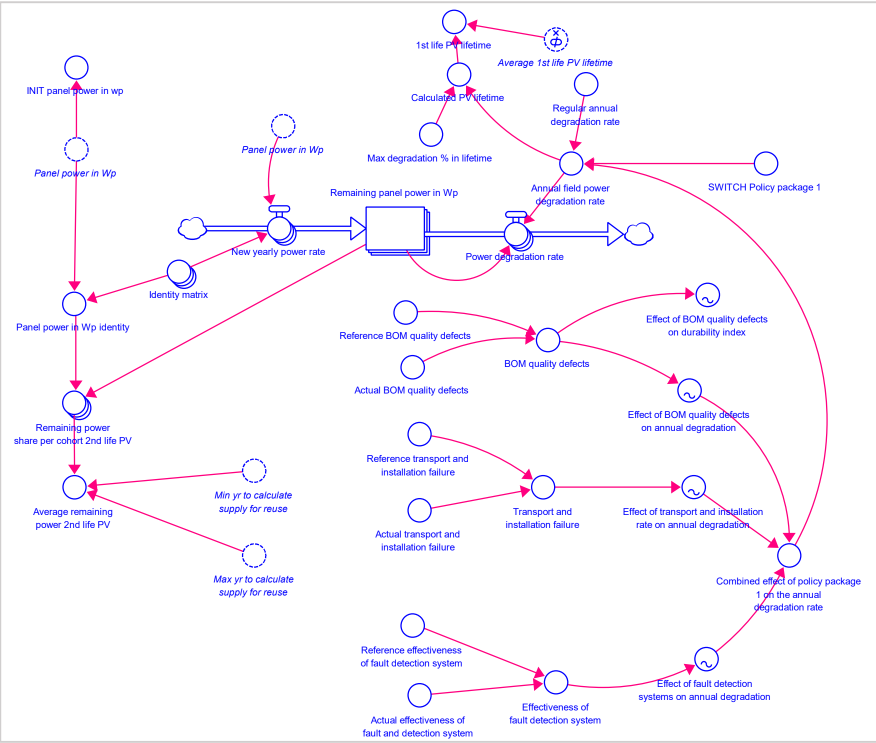

Figure 6 Extended model structure for Policy Package 1

5.1.2. MODEL RESULTS FROM POLICY PACKAGE 1

Figure 7 shows a snapshot of the model interface with selected input parameters to test Policy Package 1.

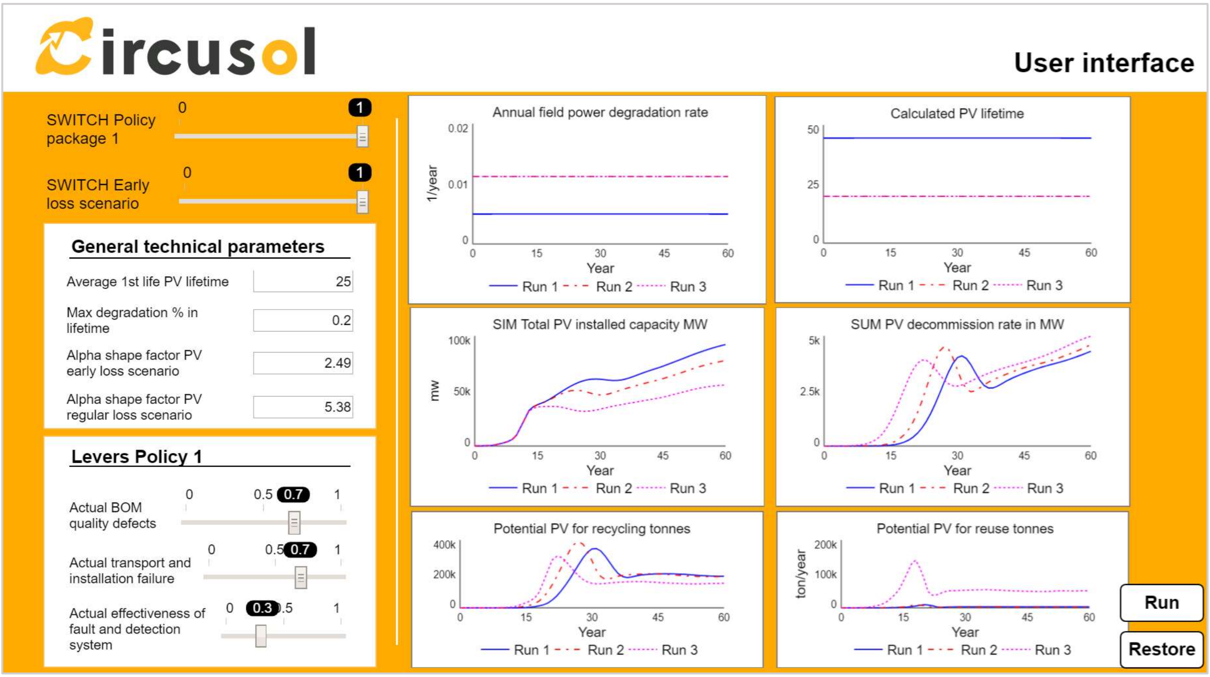

Figure 7 Model results from Policy Package 1. Run 1: Business as usual (no policy). Run 2: 20% change in levers to affect the degradation rate. Run 3: Activate early loss scenario

A summary of the results for Policy Package 1 is discussed below:

- The three parameters described above affect the PV degradation rate according to the formulation in Eq. 2.

- The degradation rate not only influences the expected PV lifetime, but also on the failure rate trajectories, the total installed capacity, the power generation capacity, and accelerates decommission rates of all ages.
- When all parameters are worsened (i.e., BOM defects increase from 0.5 to 0.7, transport and installation defects also increase from 0.5 to 0.7, and the effectiveness of the fault and detection system decrease from 0.5 to 0.3) and PV life maximization is curtailed, an important effect is observed when besides a shorter lifetime, an early loss scenario is chosen (here reuse volumes are maximized). PV lifetime in this scenario decreased below 24 yrs. Also, in run 3, when the early loss scenario is activated, meaning more failures at the beginning of lifetime coupled with a shorter lifetime, total installed capacity suffers because more panels get decommissioned earlier. In consequence, potential volumes for PV reuse, and again due to a shorter lifetime, also for recycling are boosted (see the last two output graphs from Figure 7).
- However, when policy parameters are improved, what is the frontier for lifetime maximization? In other words, how much more can PV be lifetime be extended through policy formulation?

5.2. POLICY PACKAGE 2 "MAXIMIZE PV REUSE IN 2ND LIFE"

Policy package 2 deals with the combined effect of (i) reuse collection targets, (ii) green public procurement, and (iii) standardization, labelling and warranties.

The proposal of a reuse collection target is conceptualized in the model as a percentage that affects the outflow of decommissioned PV panels. A schematic representation in Figure 9 shows how, depending on the reuse target percentage, a portion of decommissioned panels go to the reuse pipeline, whereas the remaining portion goes to the recycling pipeline. In addition, those panels that do not accumulate in the stock of "in preparation for reuse", also add up to the bulk of panels that enter the recycling pipeline. Out of the PV accumulated in the stock "in preparation for reuse", only a portion will be PV that actually is purchased for reuse. This amount will depend on: (i) the portion of PV that can be feasibly and economically repaired, (ii) an exogeneous percentage driven by green public procurement quotas, (iii) the effect of standardization, labeling and warranties on social acceptance of used PV.

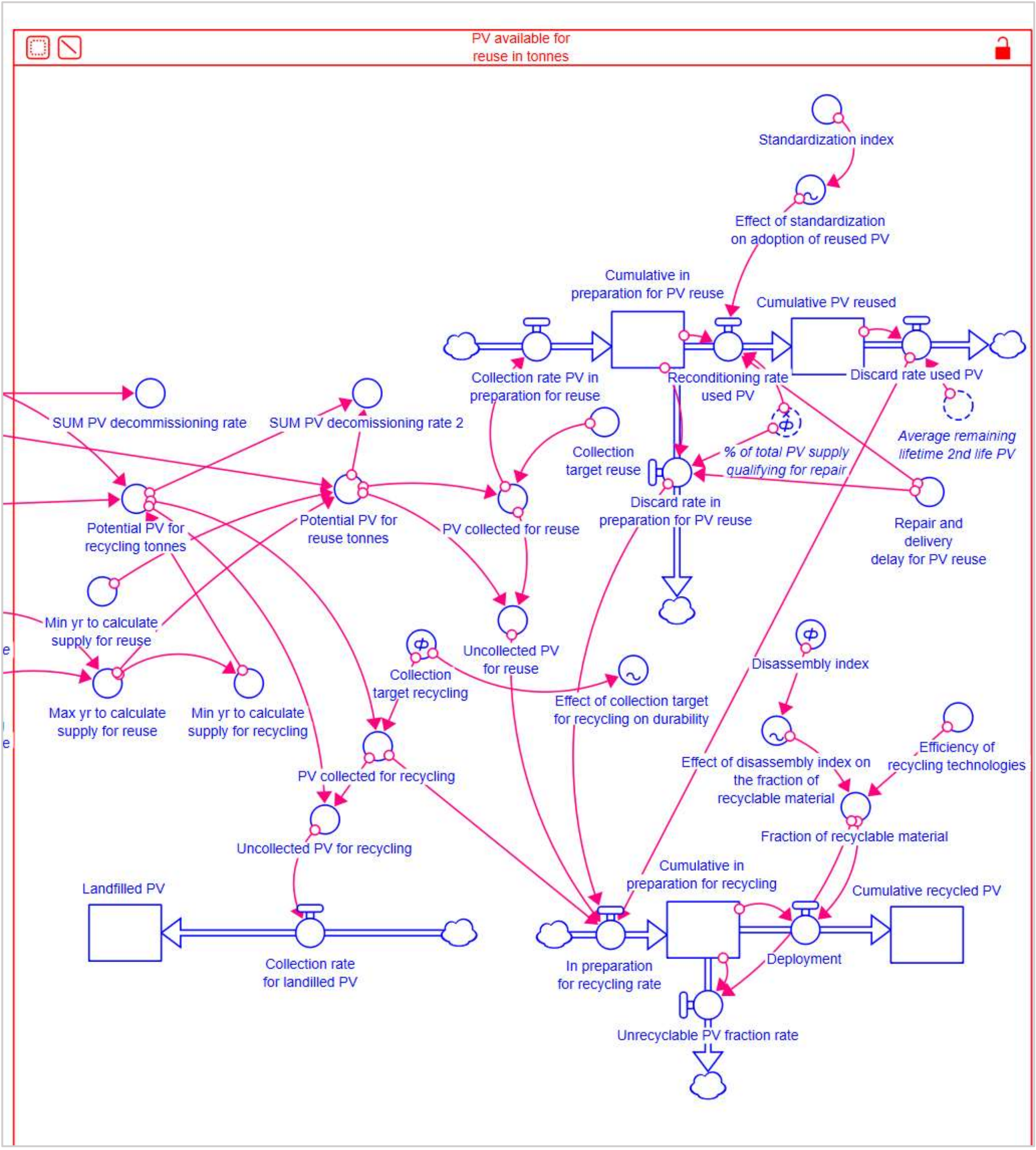

Figure 8 Extended model structure for Policy Package 2

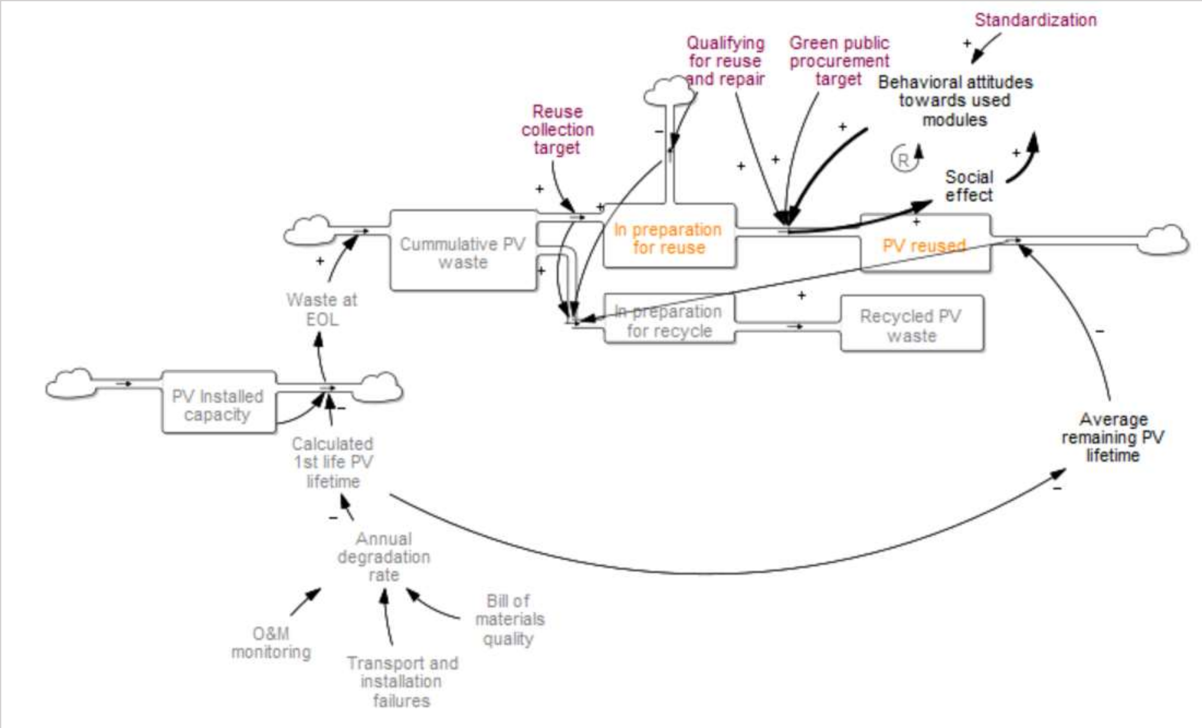

Figure 9 Schematic representation of the variables introduced in the model for Policy Package 2

Figure 10 shows a snapshot of the model interface with selected input parameters to test Policy Package 2.

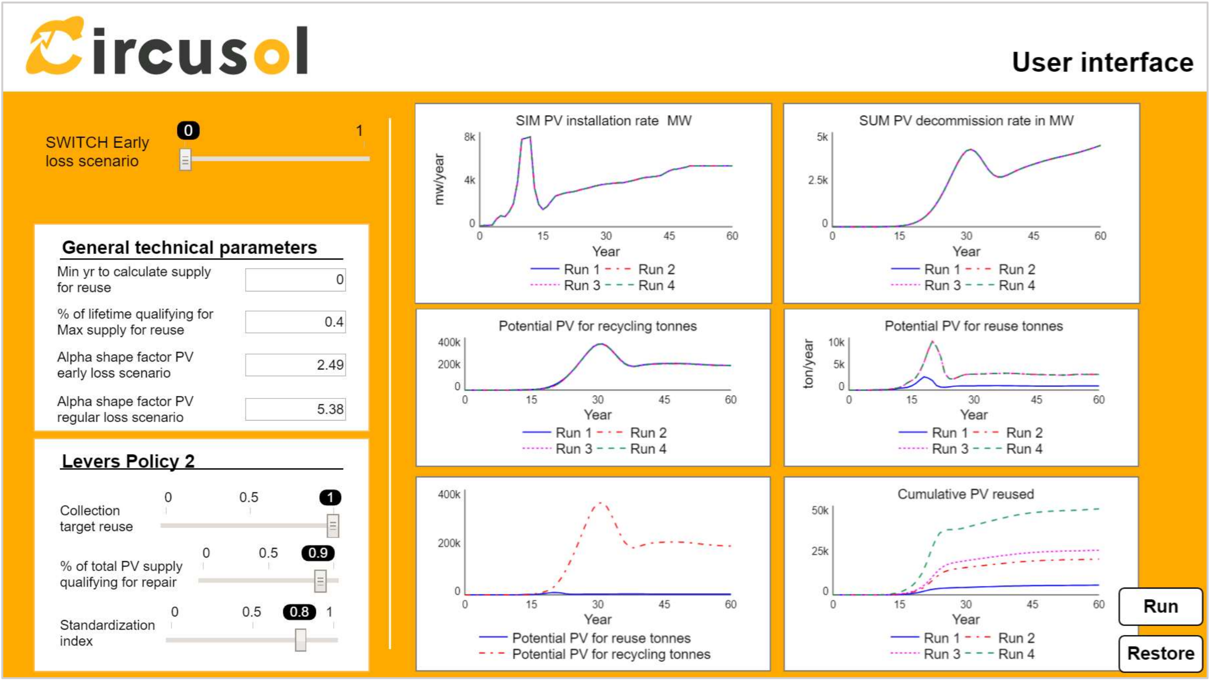

Figure 10 Model results from Policy Package 1. Run 1: Business as usual (no policy). Run 2: Increase cohort for reuse to 40% of lifetime. Run 3: Improve collection targets to 100%. Run 4: Standardization index increases from 0 to 80%

A summary of the results for Policy Package 2 is discussed below:

- Volume wise, and due to the age eligibility of PV panels for second life use (0-12 yrs old, for instance), plus shape of the installation rate, and even without imposed collection targets, the volume available for 2nd life PV is negligible when compared to the volume of older and EOL PV for recycling. This conclusion has several implications. First, and perhaps most importantly, that the amount of PV available for reuse will be sensible to the age range selected by policy makers. This means that the minimum and maximum age of PV panels that policy makers/legislation decide qualifies for a reuse will determine, up to a great extent, volumes collected for "preparation". Second, as expected, the shape of installed first life PV (e.g., exponential growth, s-shaped, overshoot and collapse, etc.) will dictate the trajectory of what can be expected in terms of available PV for reuse and later recycling. In the case of Germany, where the peak in the installation rate took place around 2012, one can observe how the "potential PV for reuse" follows a similar trajectory (adding a time delay that depends on the selected age cohort). When two previously discussed aspects are considered, one can see that the volumes one could expect for reuse are minimal when compared to the volumes expected for recycling. This is because, besides having curtailed age cohorts and installation trajectories as limiting factors for the collection of "potential PV for reuse", one must take into account other factors that continue to limit reuse further up in the pipeline: (i) actual collection targets and quotas, (ii) modules that can be economically repaired, (ii) actual market uptake of used modules. For CIRCUSOL this is of great importance since, as the simulation shows, recycling still will play a big role for the PV industry and continues to be a crucial activity that must be further developed.
- Collection targets for reuse and recycling are independent from each other and due to the current PV trajectory, recycling still takes the leading role.
- To feed the stock of "potential PV for reuse", policy values can be maximized to ensure high levels of collection, deployment and uptake of 2nd life PV.
- Finally, the peer effect of the adoption of 2nd life PV cannot be dismissed. Such social effect reflects the fact that there is a positive reinforcing effect of adoption whereby as the uptake of used PV increases, so will the willingness of other people to adopt it.

5.3. POLICY PACKAGE 3 "IMPROVE RECYCLING CONDITIONS AT EOL"

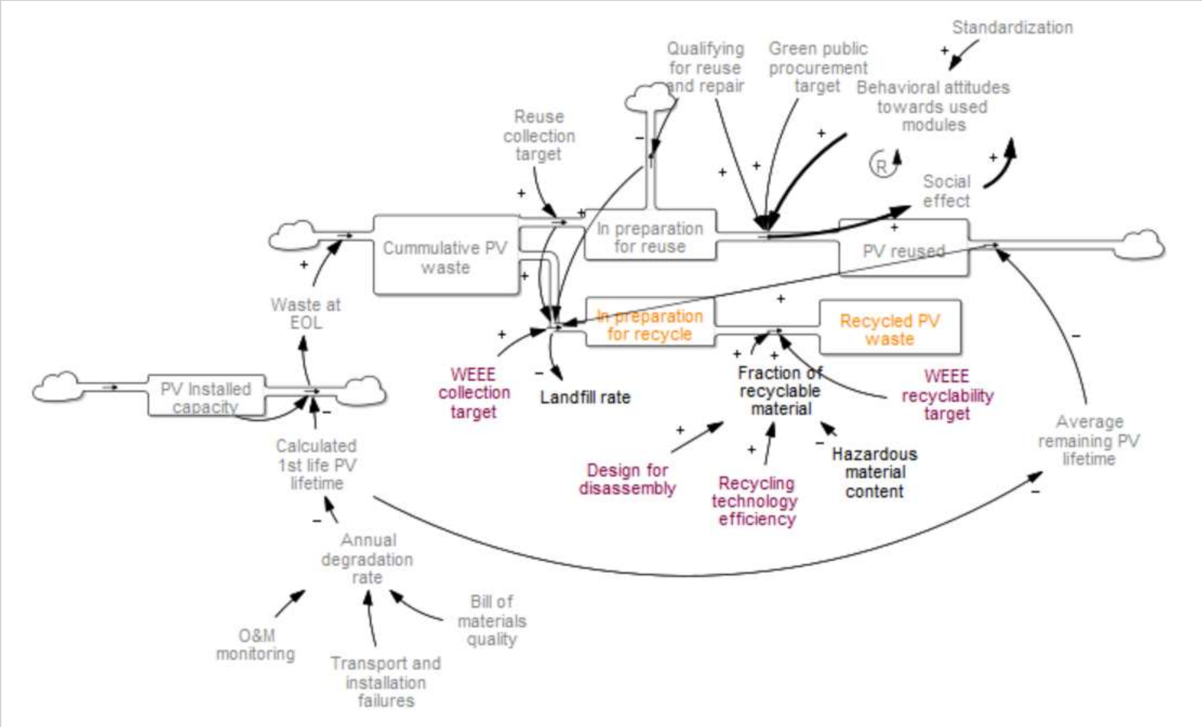

Figure 11 Schematic representation of the variables introduced in the model for Policy Package 3

Figure 12 Model results from Policy Package 3. Run 1: Business as usual (no policy). Run 2: Disassembly index from 0.7 to 1. Run 3: Collection target for recycling from 0.8 to 0.95. Run 4: Switch on Early Loss scenario.

The first leverage point for Policy Package 3 is **design for disassembly and recyclability**. DfD refers to modular product construction which facilitates separation as well as product repairability. In practice, for PV, DfD can translate to minimizing non-reversible adhesives or bonds, especially over whole surfaces and for dissimilar materials, thus facilitating disassembly and material liberation. It is assumed for this scenario that a high score in product disassembly is reflected in a high score for material separation and recovery, and in consequence, a high degree of product recyclability as well (Figure 12).

Recyclability refers to the ability to use materials, that would otherwise go to the waste stream, in a new product or reused in the same capacity for the same product. Secondary or recycled materials have the potential to reduce the environmental impact of PV (especially during the raw material extraction and manufacturing phases). The basic design of c-Si (silicon-based) modules has not changed for decades, although manufacturers have made several variations to the original design (Bilbao et al., 2021). It is this variability what affects the design and economics of recycling systems. Another factor is that the current design of PV modules requires modules to stand high temperatures and extremes environmental conditions. Such performance requirements have incentivized a design the prioritizes sealed, durable, sandwich-like structure that complicates material separation and liberation (see Table 3).

Table 3 Factors influencing material separation in PV panels

Description	Source
Variability in design from different manufacturers	Bilbao et al. (2021)
Panel architecture designed to withstand extreme weather and other environmental conditions (e.g., removing the ethylene vinyl acetate (EVA) layer or PV encapsulant, from other module components such as cells, glass, and backsheet)	Bilbao et al. (2021)

The second leverage point refers to **realistic WEEE collection and recycling targets.** The WEEE Directive 2012/19/EU is an Extended Producer Responsibility (EPR) legislation imposing collection, recovery and preparation for reuse and recycling targets for electrical and electronic equipment, including PV panels. A collection scheme for decommissioned PV installations is also included in Germany's Electrical and Electronic Equipment Act (ElektroG) since October 2015. It classifies PV modules as household appliances and regulates take-back obligations and the financing of collection and treatment. Private consumers with small systems therefore use the municipal collection (drop off) point for the free disposal of old solar panels. Only large systems are directly processed through, e.g., PV CYCLE's disposal network.

Whereas the WEEE *collection target* requires producers to collect a minimum fraction of all 1st life EOL products based upon the sales of the previous three years, the *recovery and preparation for reuse and recycling target* require producers to achieve a percentage by weight. The achievement of the targets shall be calculated, for each category, by dividing the weight of the WEEE that enters the recovery or recycling/preparing for re-use facility, after proper treatment, by the weight of all separately collected WEEE for each category, expressed as a percentage. The economics of recycling are about recovering as much as possible all materials with the Best Available Techniques Not Exceeding Excessive Costs (BATNEEC), whereby some recovered materials generate value and others generate a cost. Therefore, a waste treatment or a recycling plant shall do its utmost best to recover as much as possible separate fractions of materials to lower down the costs of the non-recyclable fractions and hence generate materials which have at a certain point a value; because not every day the value of recovered materials is positive ; in these periods the recovered materials are stored and sold at a moment where the demand and thus the prices are higher. Often forgotten is the characteristics of the waste itself. A PV Panel being a laminated flat glass product is a difficult product to recover the used materials separately than for example a glass bottle of water. The demand for higher recovery or recycling targets for PV Panels is not recommendable. More recommendable is a 'prevention of waste' target in the Extended Producer Responsibility which then takes into account the average product warranty of 12 years of PV Panels and acknowledges that PV Panels are preventing and are preventing costs for the society during many years.

The last and third leverage point refers to **more efficient R&D technologies**, which is operationalized as the efficiency in recycling. It is assumed that the material recovery rate in recycling can be, for instance, further improved by digital technologies. Labelling standardization for recyclable and non-recyclable materials, through different methods such as RFIDs, blockchain, material passports and databases (Task 3.6), can help recyclers classify feedstocks and therefore facilitate the entire recycling operation (e.g., through batch processing of categorized groups and isolation of problematic chemical compositions). Labels providing additional information beyond just material composition can also be helpful (i.e., appropriate handling and recommended repair, remanufacture, and recycle strategies).

OPERATIONALIZATION OF LEVERAGE FACTORS IN POLICY PACKAGE 3

In the model, the three elements described in the previous sections affect the so-called "Fraction of recyclable materials." This fraction of recyclable materials regulates the flow that connects the stock of "PV in preparation for recycle" with the stock of "Recycled PV" (see Figure 11). The inclusion of such a variable comes from the fact that recycling usually concentrates on the bulky materials (see Figure 13, Figure 14, and Figure 15 displaying glass, aluminum and copper, from glass cullets, Al frames, Cu wiring respectively, with recovery percentages of 100%). Hence, if a higher recycling rate is demanded from a waste stream, less bulky and more valuable parts would need to be recycled under the condition that this is economically viable for the one who must pay the costs. Examples of this is solar-grade silicon, which brings a higher revenue but also involves a more complicated and refined recycling process. Current recycling methods recover mostly low-quality, impure ferro-Si, not high-purity solar-grade Si which is needed to produce Si cells.

Material	% Recovery	Weight	Price ($/kg)	Value ($/module)	% Total
Glass	100	13.5 kg	0.10[15]	1.35	12.7
Al	100	1.83 kg	0.95[16]	1.74	16.4
Polymers	0	1.18 kg		0	0
Si	90	0.56 kg	5.52[18]	3.09	29.1
Ag	100	6.5 g	574.23[37]	3.73	35.2
Cu	100	0.11 kg	5.00[16]	0.55	5.2
Pb	100	18.3 g	1.10[16]	0.02	0.2
Sn	100	21.9 g	6.06[16]	0.13	1.2
Total				10.61	100

Figure 13 Percentage recovery of PV module components (columns 1 and 2). Taken from: Tao et al. (2020)

Material	Weight (kg)	Price ($/kg)	Value ($/module)
Glass	13.5	0.06[15]	0.81
Al	1.83	0.95[16]	1.74
Cu	0.11	5.00[16]	0.55
Total			3.10

Figure 14 Revenue of commercial recycling processes for Si modules as of October 2019. Taken from: Tao et al. (2020)

Si quality	Purity (%)	Weight (kg)	Price ($/kg)	Value ($/module)
Ferro-Si	75	0.68	0.45[23]	0.31
Metallurgical-grade Si	99	0.62	1.50[23]	0.93
Solar-grade Si	99.9999	0.56	7.58[18]	4.24
Second-grade Si	99.9999	0.56	5.52[18]	3.09

Figure 15 Revenues from Si of different qualities as of 30 October 2019. Taken from Tao et al. (2020)

A summary of the results for Policy Package 3 is discussed below:

- Evidence shows that *durability is rather inversely proportional to collection targets*. Hence, in the presence of low collection targets, more durability can be expected, whereas when faced with high, more ambitious collection targets, less durability can be expected. This is because manufacturers are indirectly either encouraged or discouraged to boost or harm product durability depending on how fast products are expected to enter the recycling stream (as dictated by legislation).
- Within the same lines, one can also argue that *durability and reliability are inversely proportional to the recyclability of PV modules*. This means that the higher the durability, the lower the recyclability potential (i.e., the more durable the PV, the harder it is to break, the more challenging the recycling). Concrete examples of this are frameless PV and EVA-based encapsulants vs silicone encapsulants. In the first case, although frameless PV makes the module lighter and easier to disassemble in preparation for recycling, it also shortens the module lifespan since it becomes more vulnerable for damage and breakage. The same happens when silicone encapsulants, an optically superior and lighter alternative,

are used instead of the more common EVA-based encapsulants, which have been used in most PV since the early 1980s.

- As portrayed in Figure 11, the "preparation for recycle" flow or rate is fed by multiple streams, namely: (i) PV eligible for reuse, but not collected, (ii) PV collected, but not processed for reuse, (iii) reused PV reaching EOL, and (iv) PV collected for recycling (based on age). Although all the previous flows contribute to the amount of PV in preparation for recycling, the last flow is the most significant one, volume wise, as shown by simulation results. This goes hand in hand with the analysis in the previous bullet points.
- Finally, if the recycling rate enforced by legislation is more stringent, more efficient technology is needed to extract materials that provide higher economic yields of more refined materials.

6. CONCLUSIONS

In addition to motivations such as a personal contribution to the energy system transformation, installations of new PV systems in Germany are largely driven by financial factors such as Feed-In-Tariffs (FITs) and the related economic profitability. Rising electricity prices are the main driver for the market uptake of new PV (also of battery systems for self-consumption). However, as evidenced by model results, even with constant electricity prices and the abolishment of government incentives, PV self-consumption is likely to gain significant market share in the future due to decreasing equipment prices.

The structure of the simulation also evidenced the extent to which the volume of available 2nd life PV is highly dependent on several factors that bear a high degree of uncertainty. These include, among others, growth rates of PV installed capacity, curves of failure rates, age cohorts selected for reuse, repair types of used PV, as well as collection and recovery rates. In particular, the volume available for "preparation for reuse" is strongly defined by the age cohort composition of the decommissioned PV and the trajectory of the installation rate in a specific location. There are, therefore, limits to the maximum amount of collected and processed PV for reuse. As evidenced by model results, recycling volumes are, in fact, still much more significant and surpass by far the volumes collected, in the best-case scenario, for reuse. This constitutes an important remark for projects like CIRCUSOL, which concentrates on the potential for PV reuse. The described results also suggest that legislative and financial support should still be given for the advancement of recycling technologies. It is currently well-known that recycling PV waste is challenging not only as a result of the high operational costs caused by the limited number of PV panels reaching their EoL, but also by the lack of well-established recycling technologies (Franco & Groesser, 2021). Finally, model results showed that the effect of switching from a regular loss scenario to an early loss scenario (when modeling failure rates for new PV) is significant. As time progresses, more data on PV failure will be available to better estimate failure curves and therefore, volumes of PV available for reuse.

Financially, LCOE results show 2nd life PV is not economically attractive when compared to new PV. In some cases, however, the willingness to pay could be high for 2nd life PV even when it is not profitable. Examples include customers driven by environmental concerns, such as in the case of the cohousing projects, or very specific market segments (e.g., hospitals, schools) for whom the influence of aesthetics and space requirements is not that strong. Other CIRCUSOL deliverables have provided empirical evidence for this (e.g., D2.3).

Policy testing scenarios showed PV panels exhibit a durability-recyclability trade-off in multiple design dimensions. Additionally, a stricter recycling target does not necessarily translate to a more recyclable product. On the contrary, high recycling quotas indirectly encourage PV manufacturers to influence durability strategies by shortening product lifetime. One suggested recommendation could be not using uniform legislative targets regarding recycling and collection rates for all product categories, but rather adapting these targets to product and market characteristics, as well as environmental impact priorities and introduce 'prevention to waste' targets. In regard to reuse, it is important to highlight also that there are other challenges not tested in this simulation model. For instance, modules of different power, efficiency, voltage, or current cannot be directly connected in series or parallel into a solar system due to mismatch losses. This means that the recyclers would have to have hundreds of large containers, each for a particular type of module with a particular efficiency. They would have to accumulate a large enough number of the same modules with the same efficiency in order to make a sale, unless they deal exclusively with waste modules from large solar farms. This would significantly increase the cost for the reused modules and affect their market uptake.

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