Supplementary Material

For the paper: Towards a Sustainable Solar Future: Forecasting Photovoltaic Waste and High-Value Recycling for France

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A. Data input

Overview of historical data, predictions and assumptions made for time varying values. Time varying values are interpolated in between data points and hold continues before first and after the last data point.

PV installation by module type: Share of Thin-Film panels

Year	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**	**2007**	**2008**	**2009**	**2010**	**2011**
Thin-Film Share	0.1	0.08	0.06	0.04	0.05	0.05	0.07	0.11	0.14	0.17	0.13	0.12
Year	**2012**	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**
Thin-Film Share	0.085	0.08	0.07	0.065	0.055	0.035	0.037	0.055	0.05	0.05	0.042	0.025
Assumption: Stable share of 0.025 after 2023, Source: (Philipps & Warmuth, 2024)												

PV installation by module type: Share of N-Type within c-Si modules
Simplification: All panels that are not thin-film panels, are c-Si-Panels, which are divided into N- and P-Type.

Year	**2013**	**2018**	**2019**	**2021**	**2023**	**2024**	**2026**	**2028**	**2029**	**2031**	**2034**
(ITRPV 10th Edition, 2019)		0.04	0.1	0.15	0.21		0.32		0.44		
(ITRPV 15th Edition, 2024)					0.3	0.62	0.8	0.88		0.91	0.92

Model input	0.03	0.04	0.1		0.3	0.62	0.8	0.88		0.91	0.92
Assumption: Stable share before 2013 and after 2034										

PV panel to power calculation

The ratio of material (in tons) to megawatt-peak in ton/MWp. Data from IRENA was used in the model.

Source/Year	2000	2005	2010	2015	2020	2025	2030	2035	2040	2045	2050
IRENA 2016	**110**	**98**	**90**	**80**	**70**	**65**	**58**	**50**	**45**	**40**	**39**
Peeters et al 2017, low scenario	108		82		60		50		38		
Peeters et al 2017, average scenario	110		85		70		55		45		
Peeters et al 2017, high scenario	123		95		75		60		48		

Material share: Silicon in c-Si Modules (Share per ton)
Own calculations based on the silicon content in gram per Watt peak and the watt to ton conversion by IRENA: Weckend et al. 2016
Assumption: Stable share after 2030.

Year	2004	2006	2008	2010	2012	2013	2014	2015
(IRENA: Weckend et al., 2016)							0.05	
(Philipps & Warmuth, 2024) in gram per Watt Peak	14g/Wp	11g/Wp	9g/Wp	7g/Wp	6.5g/Wp	6g/Wp	5.5g/Wp	5.5g/Wp
Own calculations	0.14	0.113	0.097	0.078	0.076	0.071	0.067	0.069
(Philipps & Warmuth, 2024, p. 41)								
Model input	**0.14**	**0.113**	**0.097**	**0.078**	**0.076**	**0.071**	**0.067**	**0.069**

Year	2016	2017	2018	2019	2020	2021	2022	2023	2030
(IRENA: Weckend et al., 2016)									0.03
(Philipps & Warmuth, 2024) in gram per WattPeak	5.5g/Wp	4.5g/Wp	3.5g/Wp	3.5g/Wp	3g/Wp	2.8g/Wp	2.3g/Wp	2.1g/Wp	
Own calculations	0.071	0.059	0.047	0.049	0.043	0.04	0.034	0.031	
(Philipps & Warmuth, 2024, p. 41)						0.027			
Model input	**0.071**	**0.059**	**0.047**	**0.049**	**0.043**	**0.04**	**0.034**	**0.031**	**0.03**

Material share: Other materials in c-Si-Modules (Share per ton)

Material	2004	2014	2015	2016	2018	2020	2021	2023	2030	2034	Source
Glass		0.76							0.8		(IRENA: Weckend et al., 2016)
							0.675				(Philipps & Warmuth, 2024)
Model input: Glass	**0.7**	**0.76**							**0.8**		
Aluminum		0.08							0.07		(IRENA: Weckend et al., 2016)
							0.127				(Philipps & Warmuth, 2024)
Share of panels with aluminum frame					0.95			0.92		0.8	(ITRPV 10th Edition, 2019; ITRPV 15th Edition, 2024)
Model input: Aluminum		**0.1**							**0.07**		
Copper		0.01									(IRENA: Weckend et al., 2016)
							0.013				(Philipps & Warmuth, 2024)
Model input: Copper	**0.01**									**0.01**	

Material	**2000**	**2003**	**2005**	**2006**	**2009**	**2010**	**2012**	**2014**	**2015**	**2020**	**2023**	**2030**	**2034**	**Source**
Silver	0.00218	0.00190		0.00177	0.00169		0.00148		0.00124					(Peeters et al., 2017) and Soltech 2016
Low scenario	0.002		0.0017			0.00105			0.00025	0.00008				(Peeters et al., 2017)
Average scenario	0.00215		0.00185			0.0014			0.00045	0.0002				(Peeters et al., 2017)
High scenario	0.00225		0.0019			0.0017			0.00065	0.0004				(Peeters et al., 2017)
								0.001				Slight reduction		(IRENA: Weckend et al., 2016)
Market share for silver-based metallization technology for SHJ cells											0.95	0.5	0.35	(ITRPV 15th Edition, 2024)
Model input: Silver	**0.00215**		**0.00185**			**0.0014**			**0.00045**	**0.0002**			**0.0001**	
Other materials:	**Rest of materials is result of calculations in the model**													

Comment: Peeters et al. (2017) performed a literature review on the silver content of PV panels and found the results to be highly inconsistent, with some publications describing 10 times higher content than others, and often a lack of clarity on panel source and methodology used. They developed three different scenarios for silver content based on the literature as well as data provided by Soltech.

Material share: Materials in Thin-Film Modules (Share per ton)

Material	2004	2014	2016	2018	2021	2023	2030	2034	Source
Glass (CIGS)		0.89					0.88		(IRENA: Weckend et al., 2016)
Glass (CdTe)		0.97					0.96		(IRENA: Weckend et al., 2016)
Model input: Glass		**0.92**					**0.9**		
Aluminum (CIGS)		0.07					0.08		(IRENA: Weckend et al., 2016)
Share of panels with aluminum frame				0.95		0.92		0.8	(ITRPV 10th Edition, 2019; ITRPV 15th Edition, 2024)
Model input: Aluminum		**0.06**					**0.07**		
Model input: silicon	**0**							**0**	
Model input: Copper	**0.01**							**0.01**	Assumption: Copper in connection cables similar

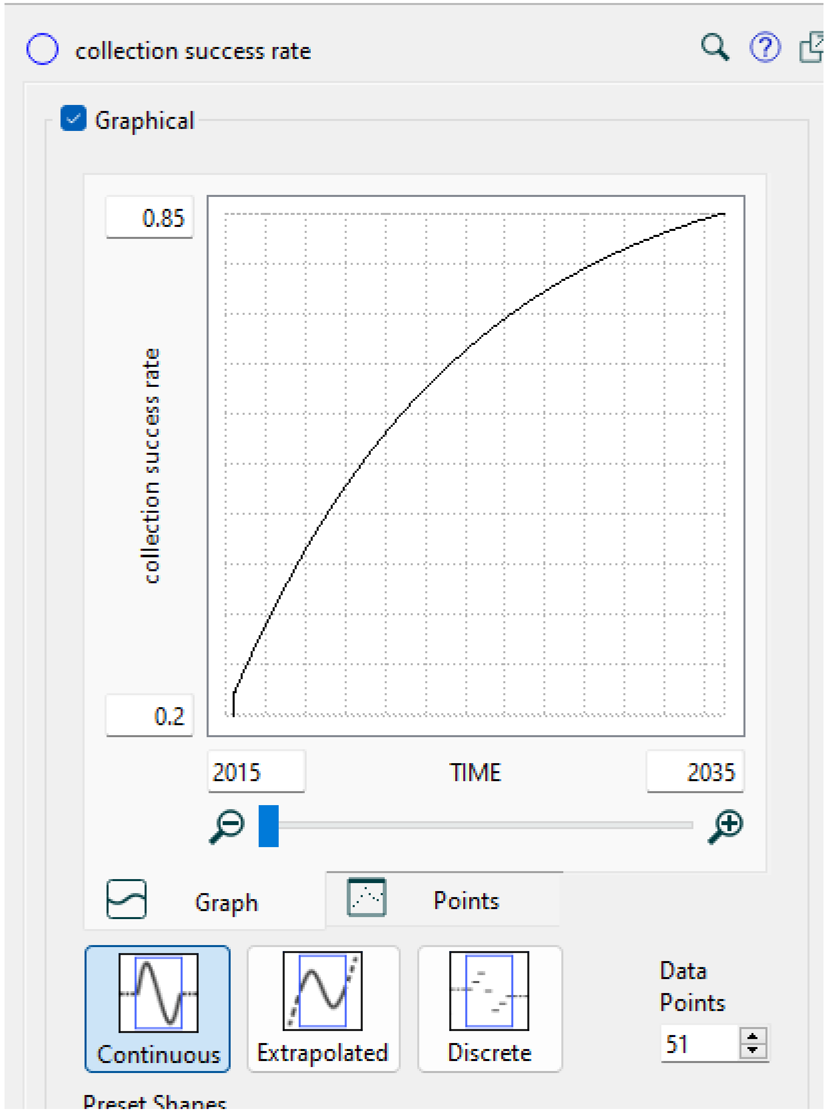
									to c-Si.Modules
Model input: Silver	**0**							**0**	
Other materials:	**Rest of materials is result of calculations in the model**								

Recycling efficiency and model assumptions
As a simplification recycling efficiencies from c-Si modules are also used for thin-film in the model and efficiencies are assumed to be stable (no learning effect).

Material	Efficency	Year	Project or Company/Method	Source
Glass	85% high quality 15% low quality	2018-2021	ReModul/ Shredding	(ReModul, 2021, p. 65)
	98% scrap Rest contaminated glass (Disposal in landfill)	2013-2015	FRELP	(Latunussa et al., 2016)
Model: High-value	85% high value 15% disposal			
Model: Standard	98% low value 1% disposal			
Aluminium	100% of Frame 0% of Backcontact 98% Overall	2018-2021	ReModul / Shredding	(ReModul, 2021, p. 65)
	98.5% scrap	2013-2015	FRELP	(Latunussa et al., 2016)
Model: High-value	98% high-value 2% disposal	Assumption: In both cases only the aluminum in the frame is recovered.		
Model: Standard	98% high-value 2% disposal			
Copper	4,5kg from connector cables 5kg from bus bar, each per ton of EoL modules No share of loss mentioned	2018-2021	ReModul/ Shredding	(ReModul, 2021, p. 65)
	4.38kg of scrap copper, No share of loss mentioned	2013-2015	FRELP	(Latunussa et al., 2016)

	83%		ASU	(Huang et al., 2017)
Model: High-value	83% high-value Rest disposal			
Model: Standard	45% high-value Rest disposal	Assumption: In standard recycling only copper in connector cables is recycled, not copper in bus bars.		
Silicon	69% in PV quality Rest loss	2018-2021	ReModul/ Shredding & leaching, No Siemens process, separate treatment of differently doped modules necessary	(ReModul, 2021, p. 65)
	At least 95%, metallurgical grade		FRELP/ leaching	(Latunussa et al., 2016)
	90% solar-grade		ASU	(Huang et al., 2017)
Model: High-value	95% metallurgical grade Rest disposal			
Model: Standard	90% downcycled Rest disposal			
Silver	300g per ton of EoL modules, No share of loss mentioned	2018-2021	ReModul/ Shredding & leaching	(ReModul, 2021, p. 65)
	94% (500g per ton)	2013-2015	FRELP	(Latunussa et al., 2016)
	74%		ASU	(Huang et al., 2017)
Model: High-value	80% recovery Rest disposal			
Model: Standard	0% recovery 100% disposal			

Collection success rate

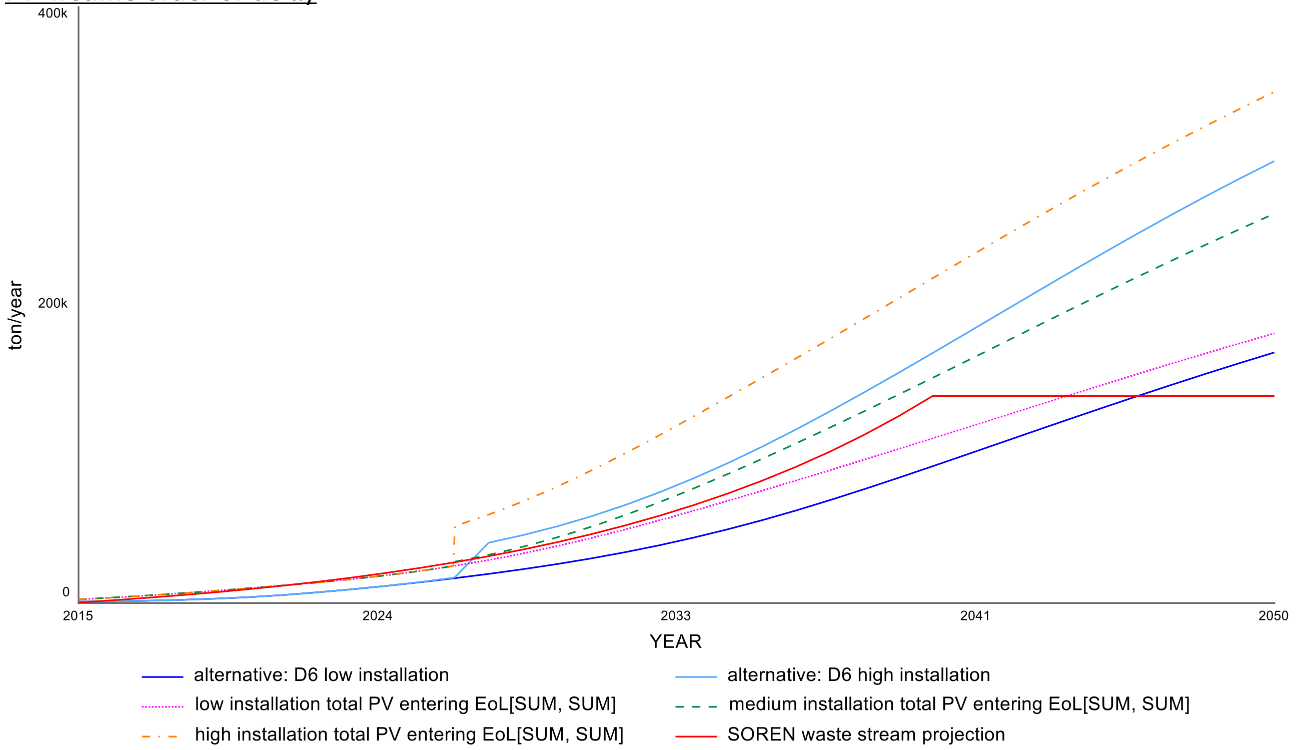


Collection success rate is assumed to be 0% until 2015 and then increases until 2035 following a logarithmic growth pattern and stays stable at 85%. 85% are based approximately on the goals for collection in set by SOREN (*Sorenewable Presentation*, 2023). SOREN plans to reach the goal earlier, but in the model we assume a lomger time span until the collection process is established enough to reach this goal.

B. Sensitivity Analysis

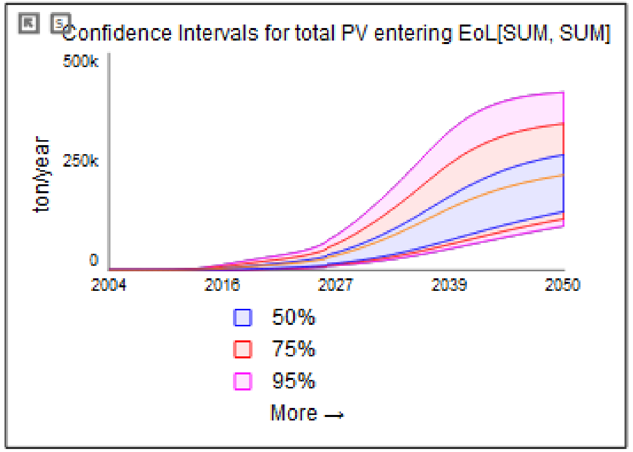
Forecasting model

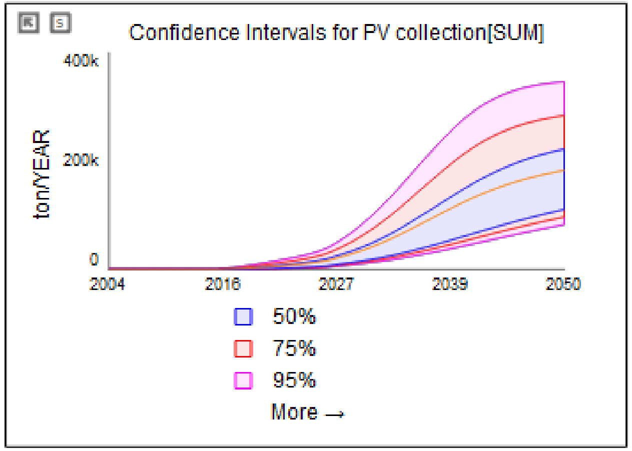
<u>PV lifetime order of delay</u>

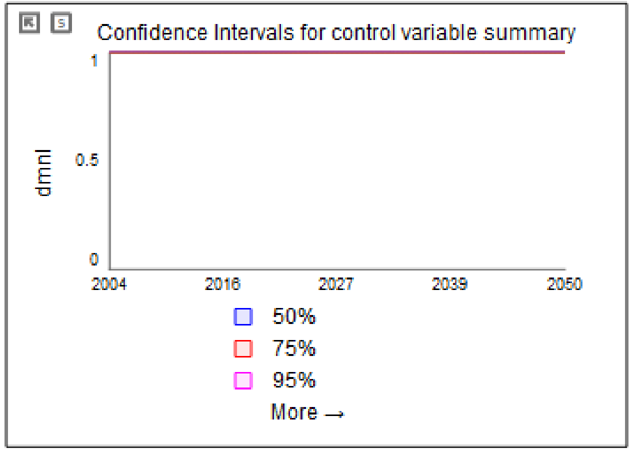


Testing a third vs sixth order delay shows the difference the variance can make for overall model behavior. The model is numerically sensitive to the change. EoL volumes increase later and are overall lower in a higher order/lower variance scenario, in both low and high installation scenarios. Later is caused by overall lower installation volumes due to lower reinstallation/replacement of old modules. Due to conflicting theoretical and empirical evidence, further investigation on the order of the delay fitting best is required to increase modle validity.

PV lifetime, 15 to 50 years, 10 runs

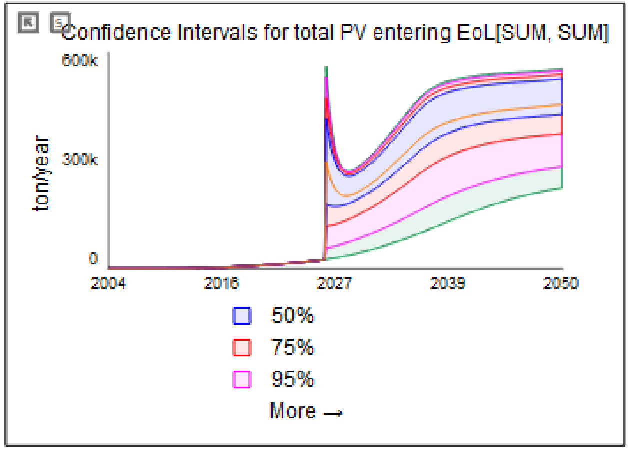


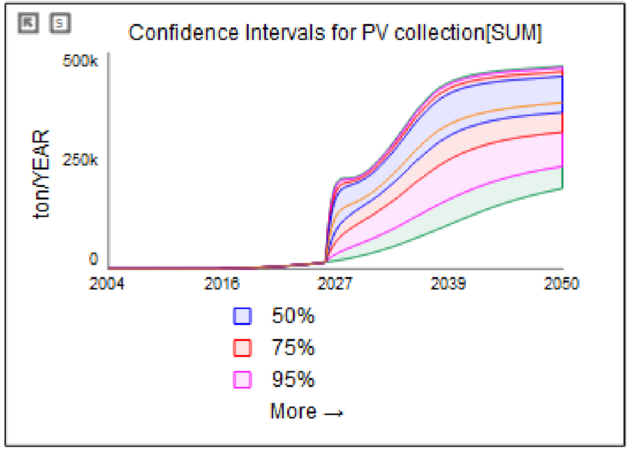


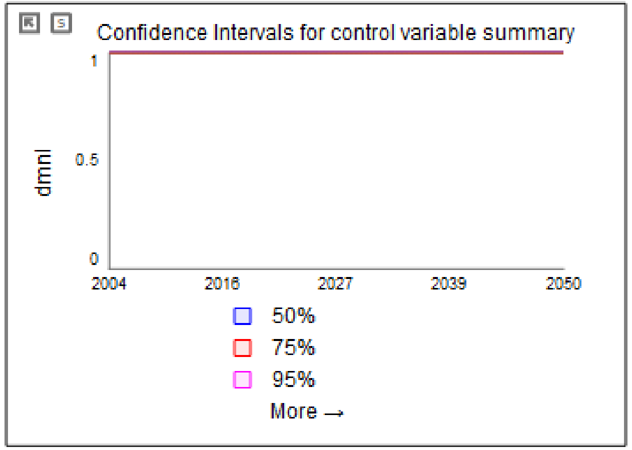


The model only reacts with numerical sensitivity, no change of behavior mode can be observed, which is expected. The control variable show that there is no deviation between the different co-flows.

Repowering share, 0 to 1 dimensionless, 10 runs





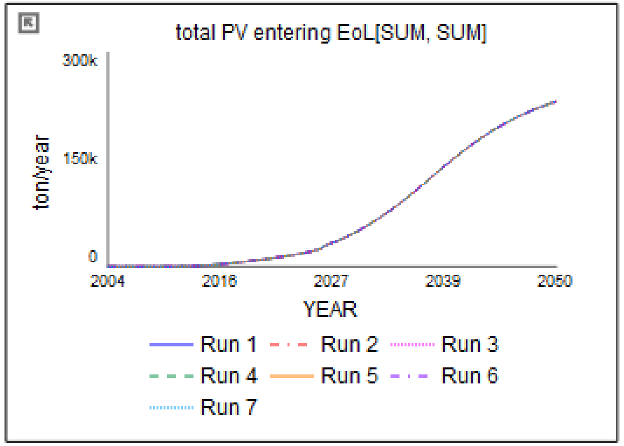


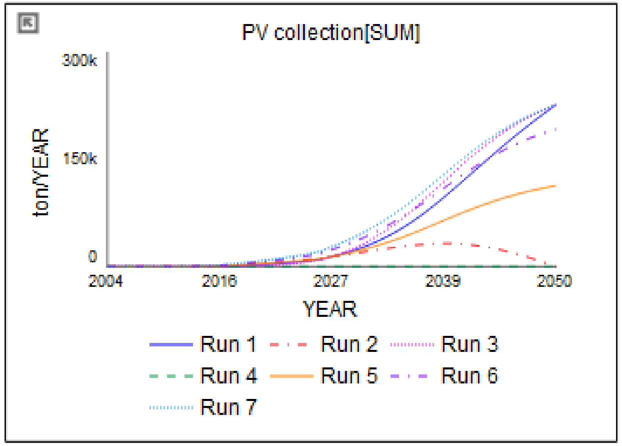
The model reacts strongly after the initial onset of the repowering in 2027, which is appropriate to the tested inputs. The control variable show that there is no deviation between the different co-flows.

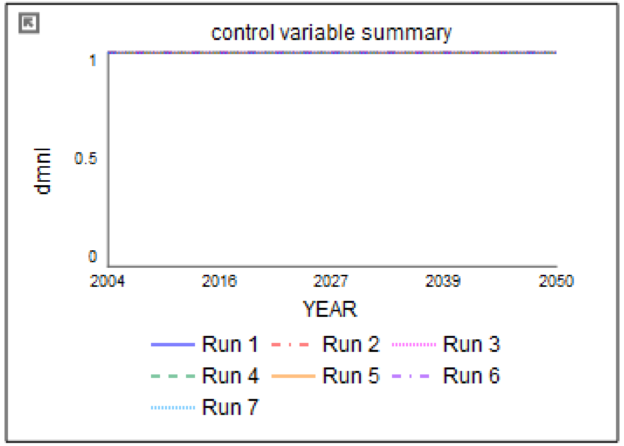
Collection success rate

Following scenarios have been tested: linear growth from 0 to 1, linear decay form 1 to 0, S-shaped growth from 0 to 1, stable rate of 0, 0.5, 0.85 and 1.

The affected variables react very sensitively, which is appropriate from a theoretical standpoint. It emphasizes the role of the collection success as a bottleneck for gathering the required volumes for the recycling industry. The collection approach and policies should be included in more detail to increase model validity.

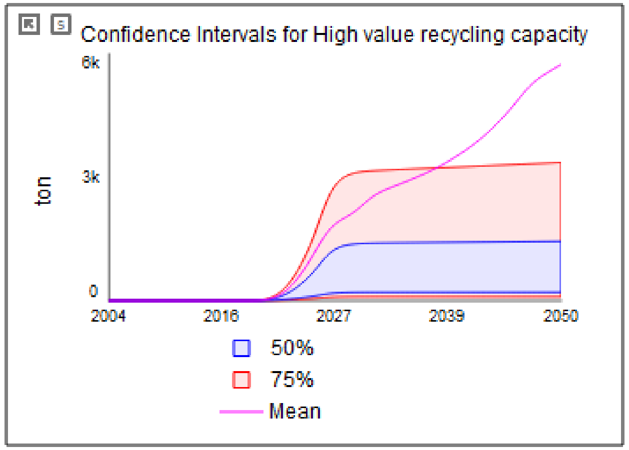


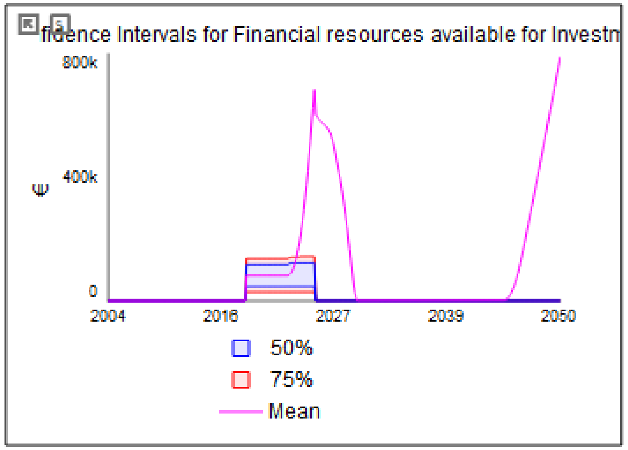


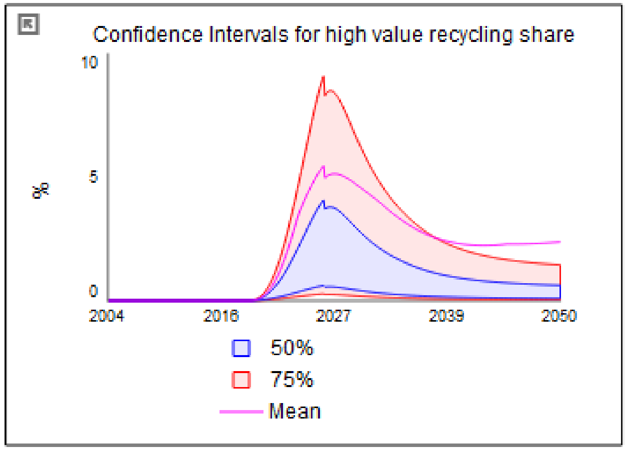


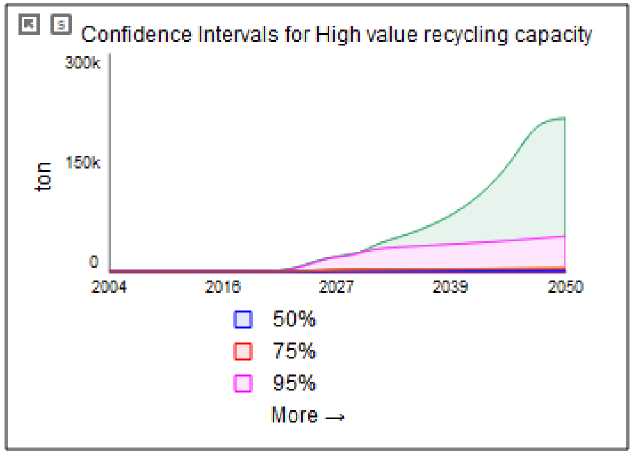
Recycling model

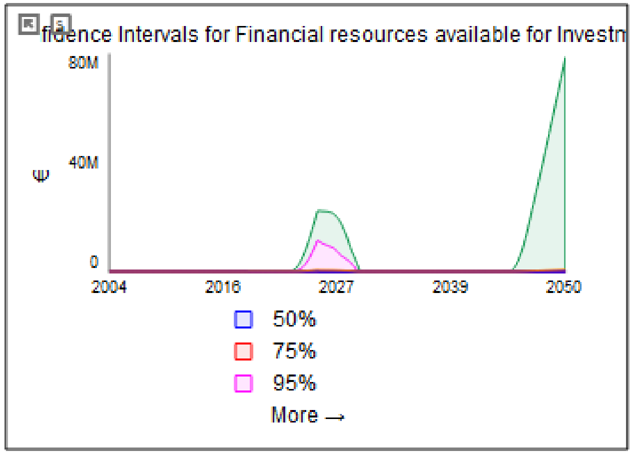
<u>Combined testing for parameters relevant to monetary values, 100 runs, investment stop time = 2025, Sobol sequence sampling:</u>
Fee per ton, 5 to 100 €/ton, uniform distribution
Yearly investment rate, 1000000 to 20000000 €/year, uniform distribution
Initial cost for capacity extension, 10000 to 1000000 €, uniform distribution

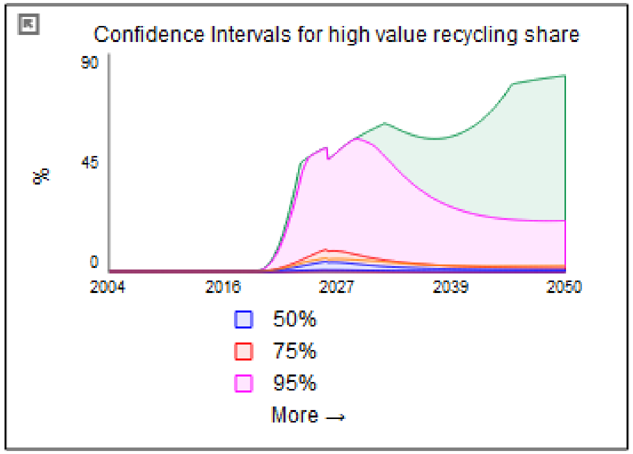






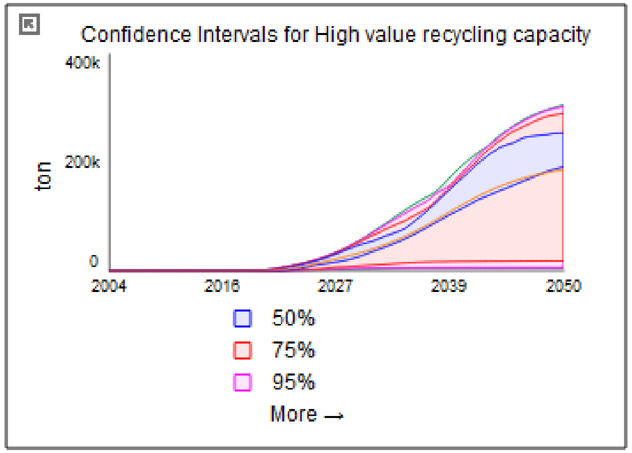


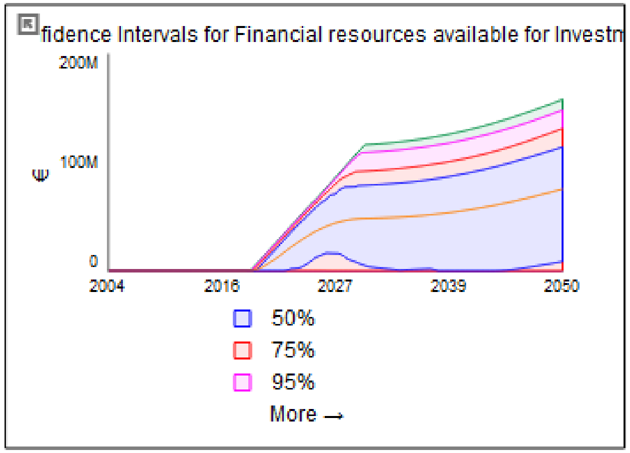


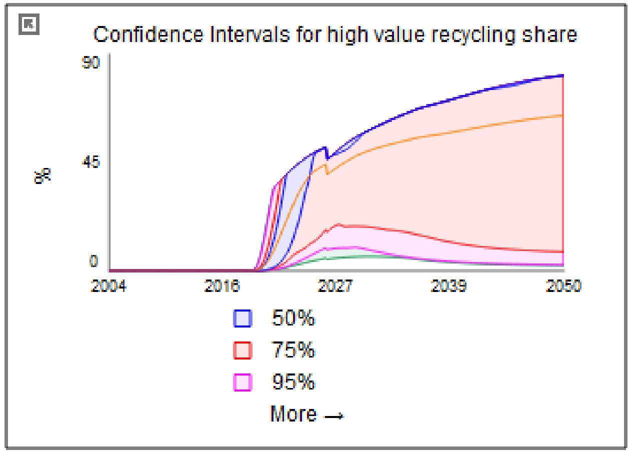


The model reacts by showing a wide variety of different behavior modes, which proves that different outcomes for the recycling industry can develop based on different financial conditions. It is appropriately sensitive to the changes.

<u>Combined testing for parameters relevant to capacity extension, 100 runs, Sobol sequence sampling:</u>
Investment stop time, 2022-2030 , uniform distribution
learning effect strength, 0-1, uniform distribution
construction delay, 1 to 7 years, uniform distribution







The model reacts by showing different behavior modes, which proves that different outcomes for the recycling industry can develop based on different financial conditions. It is appropriately sensitive to the changes.

C. Documentation

	Equation	Properties	Units	Documentation
Top-Level Model:				
cumulative_exported_PV_mat[Module_Types, Materials](t)	cumulative_exported_PV_mat[Module_Types, Materials](t - dt) + (material_export[Module_Types, Materials]) * dt	INIT cumulative_exported_PV_mat[Module_Types, Materials] = 0	ton	Sum of all exported panels arrayed by module type and material. Unit: ton.
cumulative_exported_PVs[Module_Types](t)	cumulative_exported_PVs[Module_Types](t - dt) + (export[Module_Types]) * dt	INIT cumulative_exported_PVs[Module_Types] = 0	ton	Sum of all exported panels arrayed by module type. Unit: ton.
cumulative_high_value_recycled_PVs[Module_Types](t)	cumulative_high_value_recycled_PVs[Module_Types](t - dt) + (hv_recycling[Module_Types]) * dt	INIT cumulative_high_value_recycled_PVs[Module_Types] = 0	ton	Sum of all PVs recycled via standard recycling, arrayed by module type, accumulates via the inflow standard recycling. Unit: ton
cumulative_recycled_material[Module_Types, Materials](t)	cumulative_recycled_material[Module_Types, Materials](t - dt) + (recycled_material[Module_Types, Materials]) * dt	INIT cumulative_recycled_material[Module_Types, Materials] = 0	ton	
cumulative_standard_recycled_PV[Module_Types](t)	cumulative_standard_recycled_PV[Module_Types](t - dt) + (standard_recycling[Module_Types]) * dt	INIT cumulative_standard_recycled_PV[Module_Types] = 0	ton	Sum of all PVs recycled via standard recycling, arrayed by module type, accumulates via the inflow standard recycling. Unit: ton
D6_high_cumulative_waste(t)	D6_high_cumulative_waste(t - dt) + (all_PV_entering_EoL_D6high[N, glass] + all_PV_entering_EoL_D6high[N, alu] + all_PV_entering_EoL_D6high[N, silicon] +	INIT D6_high_cumulative_waste = 0	ton	Run generated in seperate model, included for sensitivity testing

	all_PV_entering_EoL_D6high[N, cup] + all_PV_entering_EoL_D6high[N, ag] + all_PV_entering_EoL_D6high[N, others] + all_PV_entering_EoL_D6high[P, glass] + all_PV_entering_EoL_D6high[P, alu] + all_PV_entering_EoL_D6high[P, silicon] + all_PV_entering_EoL_D6high[P, cup] + all_PV_entering_EoL_D6high[P, ag] + all_PV_entering_EoL_D6high[P, others] + all_PV_entering_EoL_D6high[Thin, glass] + all_PV_entering_EoL_D6high[Thin, alu] + all_PV_entering_EoL_D6high[Thin, silicon] + all_PV_entering_EoL_D6high[Thin, cup] + all_PV_entering_EoL_D6high[Thin, ag] + all_PV_entering_EoL_D6high[Thin, others] + all_PV_entering_EoL_D6high[New, glass] + all_PV_entering_EoL_D6high[New, alu] + all_PV_entering_EoL_D6high[New, silicon] + all_PV_entering_EoL_D6high[New, cup] + all_PV_entering_EoL_D6high[New, ag] + all_PV_entering_EoL_D6high[New, others]) * dt			
D6_low_cumulative_waste(t)	D6_low_cumulative_waste(t - dt) + (all_PV_entering_EoL_D6low[N, glass] + all_PV_entering_EoL_D6low[N, alu] + all_PV_entering_EoL_D6low[N, silicon] + all_PV_entering_EoL_D6low[N, cup] + all_PV_entering_EoL_D6low[N, ag] + all_PV_entering_EoL_D6low[N, others] + all_PV_entering_EoL_D6low[P, glass] + all_PV_entering_EoL_D6low[P, alu] + all_PV_entering_EoL_D6low[P, silicon] + all_PV_entering_EoL_D6low[P, cup] + all_PV_entering_EoL_D6low[P, ag] + all_PV_entering_EoL_D6low[P, others] + all_PV_entering_EoL_D6low[Thin, glass] +	INIT D6_low_cumulative_waste = 0	ton	Run generated in seperate model, included for sensitivity testing

	all_PV_entering_EoL_D6low[Thin, alu] + all_PV_entering_EoL_D6low[Thin, silicon] + all_PV_entering_EoL_D6low[Thin, cup] + all_PV_entering_EoL_D6low[Thin, ag] + all_PV_entering_EoL_D6low[Thin, others] + all_PV_entering_EoL_D6low[New, glass] + all_PV_entering_EoL_D6low[New, alu] + all_PV_entering_EoL_D6low[New, silicon] + all_PV_entering_EoL_D6low[New, cup] + all_PV_entering_EoL_D6low[New, ag] + all_PV_entering_EoL_D6low[New, others]) * dt			
disposed_materials_hv_rec[Materials](t)	disposed_materials_hv_rec[Materials](t - dt) + (other_hv_waste_occurence[Materials]) * dt	INIT disposed_materials_hv_rec[Materials] = 0	ton	Cumulative disposed material from high-value recycling.
disposed_materials_standard[Materials](t)	disposed_materials_standard[Materials](t - dt) + (other_waste_occurrence[Materials]) * dt	INIT disposed_materials_standard[Materials] = 0	ton	Cumulative disposed material from standard recycling.
EoL_PV[Module_Types](t)	EoL_PV[Module_Types](t - dt) + (PV_entering_EoL_D3[Module_Types] + repowering_D3[Module_Types] - export[Module_Types] - PV_collection[Module_Types]) * dt	INIT EoL_PV[Module_Types] = 0	ton	PV modules that entered EoL either by aging out of their useful life or through repowering, that are not yet fed into a disposal system. The stock drains when the modules are assigned different EoL pathways: Export or official collection. Unit: ton.
EoL_PV_material[Module_Types, Materials](t)	EoL_PV_material[Module_Types, Materials](t - dt) + ("PV_mat_entering_EoL_D*"[Module_Types, Materials] + repowering_mat_D3[Module_Types, Materials] - material_export[Module_Types, Materials] - material_collection[Module_Types, Materials]) * dt	INIT EoL_PV_material[Module_Types, Materials] = 0	ton	Equivalent to EoL PVs but with additional dimensions for material, as part of the material co-flow structure. Inflows: PV mat enetring EoL and repowering 2. Outflows: material export and material collection. Unit: ton

Financial_resources_available_for_Investment(t)	Financial_resources_available_for_Investment(t - dt) + (yearly_available_resources - investments_into_capacity) * dt	INIT Financial_resources_available_for_Investment = 0	€	
High_value_recycling_capacity(t)	High_value_recycling_capacity(t - dt) + (recycling_capacity_extension) * dt	INIT High_value_recycling_capacity = 0	ton	Volume of PV that can be recycled at the same time, given the recycling time of 1 year. Capacity wear out is not included for simplification reasons. Accumulates via the inflow recycling capacity extension. Initial value: 0; Unit: ton
hv_other_materials[Materials](t)	hv_other_materials[Materials](t - dt) + (hv_mterial_recycling[Materials]) * dt	INIT hv_other_materials[Materials] = 0	ton	The stock represents the cumulative recovered materials (except silicon) in high value recycling. It sumps up each material for all module types.
low_qual_materials[Materials](t)	low_qual_materials[Materials](t - dt) + (material_downcycling[Materials]) * dt	INIT low_qual_materials[Materials] = 0	ton	The stock represents the cumulative recovered materials of low quality in standard recycling. It sumps up each material for all module types.
MW_of_PV_agegroup_1(t)	MW_of_PV_agegroup_1(t - dt) + (accounting_mw_installed - MW_PV_ageing_1) * dt	INIT MW_of_PV_agegroup_1 = 0	MW	Counterpart to PV in use 1 in module co-flow.
MW_of_PV_agegroup_2(t)	MW_of_PV_agegroup_2(t - dt) + (MW_PV_ageing_1 - MW_PV_ageing_2 - repowering_outflow) * dt	INIT MW_of_PV_agegroup_2 = 0	MW	Counterpart to PV in use 2 in module co-flow.
MW_of_PV_agegroup_3(t)	MW_of_PV_agegroup_3(t - dt) + (MW_PV_ageing_2 - accounting_PV_MW_wear_out) * dt	INIT MW_of_PV_agegroup_3 = 0	MW	Counterpart to PV in use 3 in module co-flow.
N_type_silicon[Materials](t)	N_type_silicon[Materials](t - dt) + (N_type_recycling[Materials]) * dt	INIT N_type_silicon[Materials] = 0	ton	The stock represents the cumulative recovered negatively doped silicon from EoL PVs in high value recycling.

P_Type_silicon[Materials](t)	P_Type_silicon[Materials](t - dt) + (P_silicon_recycling[Materials]) * dt	INIT P_Type_silicon[Materials] = 0	ton	The Stock represents the cumulative recovered positively doped silicon from EoL PVs in high-value recycling
PV_available_for_recycling[Module_Types](t)	PV_available_for_recycling[Module_Types](t - dt) + (PV_collection[Module_Types] - hv_recycling[Module_Types] - standard_recycling[Module_Types]) * dt	INIT PV_available_for_recycling[Module_Types] = 0	ton	EoL PV arrayed by module type that are available for recycling. The stock accumulates via collection and drains through recycling. Panels have two different options for recycling: high-value recycling (hv recycling) or standard recycling. Unit: ton
PV_in_use_1[Module_Types](t)	PV_in_use_1[Module_Types](t - dt) + (annual_PV_installation_in_tons[Module_Types] - PV_aging_1[Module_Types]) * dt	INIT PV_in_use_1[Module_Types] = 0	ton	This stock includes all PVs in the first third of their lifetime, arrayed by module type. It accumulates via annual PV installation in tons and drains via PV aging 1. Unit: ton
PV_in_use_2[Module_Types](t)	PV_in_use_2[Module_Types](t - dt) + (PV_aging_1[Module_Types] - PV_aging_2[Module_Types] - repowering_D3[Module_Types]) * dt	INIT PV_in_use_2[Module_Types] = 0	ton	This stock includes all PVs in the second third of their lifetime, arrayed by module type. It accumulates via aPV aging 1 and drains via PV aging 2 and depending on the scenario via repowering. Unit: ton
PV_in_use_3[Module_Types](t)	PV_in_use_3[Module_Types](t - dt) + (PV_aging_2[Module_Types] - PV_entering_EoL_D3[Module_Types]) * dt	INIT PV_in_use_3[Module_Types] = 0	ton	This stock includes all PVs in the last third of their lifetime, arrayed by module type. It accumulates via PV aging 2 and drains via PV entering EoL. Unit: ton

PV_mat_available_for_recycling[Module_Types, Materials](t)	PV_mat_available_for_recycling[Module_Types, Materials](t - dt) + (material_collection[Module_Types, Materials] - recycled_material[Module_Types, Materials]) * dt	INIT PV_mat_available_for_recycling[Module_Types, Materials] = 0	ton	EoL PV arrayed by module type and material that are available for recycling. The stock accumulates via material collection and drains through recycled material. Unit: ton
PV_material_in_use_1[Module_Types, Materials](t)	PV_material_in_use_1[Module_Types, Materials](t - dt) + (PV_installation_by_material[Module_Types, Materials] - PV_mat_aging_1[Module_Types, Materials]) * dt	INIT PV_material_in_use_1[Module_Types, Materials] = 0	ton	Equivalent to PV in use 1 but with additional dimensions for material, as part of the material co-flow structure. Unit: ton
PV_material_in_use_2[Module_Types, Materials](t)	PV_material_in_use_2[Module_Types, Materials](t - dt) + (PV_mat_aging_1[Module_Types, Materials] - PV_mat_aging_2[Module_Types, Materials] - repowering_mat_D3[Module_Types, Materials]) * dt	INIT PV_material_in_use_2[Module_Types, Materials] = 0	ton	Equivalent to PV in use 2 but with additional dimensions for material, as part of the material co-flow structure. Unit: ton
PV_material_in_use_3[Module_Types, Materials](t)	PV_material_in_use_3[Module_Types, Materials](t - dt) + (PV_mat_aging_2[Module_Types, Materials] - "PV_mat_entering_EoL_D*"[Module_Types, Materials]) * dt	INIT PV_material_in_use_3[Module_Types, Materials] = 0	ton	Equivalent to PV in use 3 but with additional dimensions for material, as part of the material co-flow structure. Unit: ton
SOREN_cumulative_PV_waste(t)	SOREN_cumulative_PV_waste(t - dt) + (accounting_SOREN) * dt	INIT SOREN_cumulative_PV_waste = 0	ton	
standard_rec_materials[Materials](t)	standard_rec_materials[Materials](t - dt) + (standard_material_recycling[Materials]) * dt	INIT standard_rec_materials[Materials] = 0	ton	The stock represents the cumulative recovered materials of high quality in standard recycling. It sumps up each material for all module types.
total_mass_of_EoL_PV[Module_Types, Materials](t)	total_mass_of_EoL_PV[Module_Types, Materials](t - dt) +	INIT total_mass_of_EoL_PV	ton	

	(total_PV_entering_EoL[Module_Types, Materials]) * dt	[Module_Types, Materials] = 0		
total_sepnding_on_hq_recycling(t)	total_sepnding_on_hq_recycling(t - dt) + (total_yearly_spending_on_hv_recycling) * dt	INIT total_sepnding_on_hq_recycling = 0	€	
accounting_mw_installed	annual_PV_installation_in_MW		Mw/year	Counterpart to annual PV installations in module co-flow.
accounting_PV_MW_wear_out	MW_of_PV_agegroup_3/(PV_lifetime/3)		Mw/year	Counterpart to flow PV enetring EoL in module co-flow.
accounting_SOREN	SOREN_waste_stream_projection		ton/YEAR	
all_PV_entering_EoL_D6high[Module_Types, Materials]	NAN		ton/year	Run generated in seperate model, included for sensitivity testing
all_PV_entering_EoL_D6low[Module_Types, Materials]	NAN		ton/year	Run generated in seperate model, included for sensitivity testing
annual_PV_installation_in_tons[Module_Types]	panel_to_power_ratio*annual_PV_installation_by_module_type		ton/YEAR	Annual PV installation in tons arrayed by module calculated by multiplying the annual PV installation by module type with the panel to power ratio. Therefore it is assumed that all module types have the same panel to power ratio. It is also the inflow to the stock PV in use 1, it represents the modules that are installed in a year. Unit: Tons per Year.
export[Module_Types]	EoL_PV[Module_Types]*(1-collection_success_rate)		ton/year	EoL modules arrayed by module that are exported each year to outside of France (EU and non-EU). It is assumed that all panels that are not collected are exported.

				The unit is ton per year.
hv_mterial_recycling[glass]	(recycled_material[N,glass]*(hv_recycling[N]//SUM(recycled_material[N,*])) + recycled_material[P,glass]*(hv_recycling[P]//SUM(recycled_material[P,*])) + recycled_material[Thin,glass]*(hv_recycling[Thin]//SUM(recycled_material[Thin,*])) + recycled_material[New,glass]*(hv_recycling[New]//SUM(recycled_material[New,*]))) * hv_recycling_efficiency[glass]		ton/year	The flow represents the annual recovered materials (except silicon) in high value recycling. It sumps up each material for all module types. The successfully recycled material per year and module type is calculated by multiplying the total material in recycling (the specific material and module dimension of the recycled material flow of the material co-flow) with the share of the share of the specific module type that got into hv recycling and the hv recycling efficiency (representing how much of the existing material can be recovered). The result for each module type is than added up to get the overall recovered volume for each material.
hv_mterial_recycling[alu]	(recycled_material[N,alu]*(hv_recycling[N]//SUM(recycled_material[N,*])) + recycled_material[P,alu]*(hv_recycling[P]//SUM(recycled_material[P,*])) + recycled_material[Thin,alu]*(hv_recycling[Thin]//SUM(recycled_material[Thin,*])) + recycled_material[New,alu]*(hv_recycling[New]//SUM(recycled_material[New,*]))) * hv_recycling_efficiency[alu]			
hv_mterial_recycling[silicon]	0			
hv_mterial_recycling[cup]	(recycled_material[N,cup]*(hv_recycling[N]//SUM(recycled_material[N,*])) + recycled_material[P,cup]*(hv_recycling[P]//SUM(recycled_material[P,*])) +			

	recycled_material[Thin,cup]*(hv_recycling[Thin]//SUM(recycled_material[Thin,*])) + recycled_material[New,cup]*(hv_recycling[New]//SUM(recycled_material[New,*]))) * hv_recycling_efficiency[cup]			
hv_mterial_recycling[ag]	(recycled_material[N,ag]*(hv_recycling[N]//SUM(recycled_material[N,*])) + recycled_material[P,ag]*(hv_recycling[P]//SUM(recycled_material[P,*])) + recycled_material[Thin,ag]*(hv_recycling[Thin]//SUM(recycled_material[Thin,*])) + recycled_material[New,ag]*(hv_recycling[New]//SUM(recycled_material[New,*]))) * hv_recycling_efficiency[ag]			
hv_mterial_recycling[others]	(recycled_material[N,others]*(hv_recycling[N]//SUM(recycled_material[N,*])) + recycled_material[P,others]*(hv_recycling[P]//SUM(recycled_material[P,*])) + recycled_material[Thin,others]*(hv_recycling[Thin]//SUM(recycled_material[Thin,*])) + recycled_material[New,others]*(hv_recycling[New]//SUM(recycled_material[New,*]))) * hv_recycling_efficiency[others]			
hv_recycling[Module_Types]	(ALLOCATE(High_value_recycling_capacity, Module_Types, PV_available_for_recycling, Priority[*], Spread))/recycling_processing_time		ton/YEAR	
investments_into_capacity	MIN((actual_cost_per_additional_capacity_unit*capacity_gap)/time_to_invest, Financial_resources_available_for_Investment/DT)		€/year	Money invested in a year, based on capacity gap and cost for additional cpacity, drains the stock Financial resources available for investment.
material_collection[Module_Types, Materials]	EoL_PV_material*collection_success_rate		ton/YEAR	PV modules that follow the official collection path, arrayed by module type and material, depending on the panels

				that reached end of life and the collection success rate. Is part of the material co-flow structure and equivalent to PV collection. Outflow of EoL PV and inflow to PV available for recycling. Unit
material_downcycling[glass]	(recycled_material[N,glass]*(standard_recycling[N]//SUM(recycled_material[N,*])) + recycled_material[P,glass]*(standard_recycling[P]//SUM(recycled_material[P,*])) + recycled_material[Thin,glass]*(standard_recycling[Thin]//SUM(recycled_material[Thin,*])) + recycled_material[New,glass]*(standard_recycling[New]//SUM(recycled_material[N,*]))) * downcycling_efficiency[glass]		ton/year	The flow represents the annual recovered materials of low quality in standard recycling. It sumps up each material for all module types. The successfully recycled material per year and module type is calculated by multiplying the total material in recycling (the specific material and module dimension of the recycled material flow of the material co-flow) with the share of the share of the specific module type that got into standard recycling and the downcycling efficiency (representing how much of the existing material can be recovered in lower quality). The result for each module type is than added up to get the overall recovered volume for each material.
material_downcycling[alu]	(recycled_material[N,alu]*(standard_recycling[N]//SUM(recycled_material[N,*])) + recycled_material[P,alu]*(standard_recycling[P]//SUM(recycled_material[P,*])) + recycled_material[Thin,alu]*(standard_recycling[Thin]//SUM(recycled_material[Thin,*])) + recycled_material[New,alu]*(standard_recyclin			

	g[New]//SUM(recycled_material[New,*]))) * downcycling_efficiency[alu]			
material_downcycling[silicon]	(recycled_material[N,silicon]*(standard_recycling[N]//SUM(recycled_material[N,*])) + recycled_material[P,silicon]*(standard_recycling[P]//SUM(recycled_material[P,*])) + recycled_material[Thin,silicon]*(standard_recycling[Thin]//SUM(recycled_material[Thin,*])) + recycled_material[New,silicon]*(standard_recycling[New]//SUM(recycled_material[New,*]))) * downcycling_efficiency[silicon]			
material_downcycling[cup]	(recycled_material[N,cup]*(standard_recycling[N]//SUM(recycled_material[N,*])) + recycled_material[P,cup]*(standard_recycling[P]//SUM(recycled_material[P,*])) + recycled_material[Thin,cup]*(standard_recycling[Thin]//SUM(recycled_material[Thin,*])) + recycled_material[New,cup]*(standard_recycling[New]//SUM(recycled_material[New,*]))) * downcycling_efficiency[cup]			
material_downcycling[ag]	(recycled_material[N,ag]*(standard_recycling[N]//SUM(recycled_material[N,*])) + recycled_material[P,ag]*(standard_recycling[P]//SUM(recycled_material[P,*])) + recycled_material[Thin,ag]*(standard_recycling[Thin]//SUM(recycled_material[Thin,*])) + recycled_material[New,ag]*(standard_recycling[New]//SUM(recycled_material[New,*]))) * downcycling_efficiency[ag]			
material_downcycling[others]	(recycled_material[N,others]*(standard_recycling[N]//SUM(recycled_material[N,*])) + recycled_material[P,others]*(standard_recycling[P]//SUM(recycled_material[P,*])) + recycled_material[Thin,others]*(standard_recy			

	cling[Thin]//SUM(recycled_material[Thin,*])) + recycled_material[New,others]*(standard_recycling[New]//SUM(recycled_material[New,*]))) * downcycling_efficiency[others]			
material_export[Module_Types, Materials]	EoL_PV_material*(1-collection_success_rate)		ton/year	EoL modules arrayed by module and material that are exported each year to outside of France (EU and non-EU). It is assumed that all panels that are not collected are exported. The unit is ton per year.
MW_PV_ageing_1	MW_of_PV_agegroup_1/(PV_lifetime/3)		Mw/year	
MW_PV_ageing_2	MW_of_PV_agegroup_2/(PV_lifetime/3)		Mw/year	
N_type_recycling[glass]	0		ton/year	The flow represents the annual recovered negatively doped silicon from EoL PVs in high value recycling. The successfully recycled material per year is calculated by multiplying the total material in recycling (the specific material and module dimension of the recycled material flow of the material co-flow) with the share of the share of the specific module type that got into hv recycling and the hv recycling efficiency (representing how much of the existing material can be recovered). The unit is ton per year.
N_type_recycling[alu]	0			

N_type_recycling[silicon]	recycled_material[N,silicon]*(hv_recycling[N]//SUM(recycled_material[N,*]))*hv_recycling_efficiency[silicon]			
N_type_recycling[cup]	0			
N_type_recycling[ag]	0			
N_type_recycling[others]	0			
other_hv_waste_occurence[glass]	(recycled_material[N,glass]*(hv_recycling[N]//SUM(recycled_material[N,*])) + recycled_material[P,glass]*(hv_recycling[P]//SUM(recycled_material[P,*])) + recycled_material[Thin,glass]*(hv_recycling[Thin]//SUM(recycled_material[Thin,*])) + recycled_material[New,glass]*(hv_recycling[New]//SUM(recycled_material[New,*]))) * hv_recycling_waste_share[glass]		ton/year	Represents the annual stream of materials that cannot be recycled in high-value recycling and needs to be disposed.
other_hv_waste_occurence[alu]	(recycled_material[N,alu]*(hv_recycling[N]//SUM(recycled_material[N,*])) + recycled_material[P,alu]*(hv_recycling[P]//SUM(recycled_material[P,*])) + recycled_material[Thin,alu]*(hv_recycling[Thin]//SUM(recycled_material[Thin,*])) + recycled_material[New,alu]*(hv_recycling[New]//SUM(recycled_material[New,*]))) * hv_recycling_waste_share[alu]			
other_hv_waste_occurence[silicon]	(recycled_material[N,silicon]*(hv_recycling[N]// SUM(recycled_material[N,*])) + recycled_material[P,silicon]*(hv_recycling[P]//SUM(recycled_material[P,*])) + recycled_material[Thin,silicon]*(hv_recycling[Thin]//SUM(recycled_material[Thin,*])) + recycled_material[New,silicon]*(hv_recycling[New]//SUM(recycled_material[New,*]))) * hv_recycling_waste_share[silicon]			

other_hv_waste_occurence[cup]	(recycled_material[N,cup]*(hv_recycling[N]//SUM(recycled_material[N,*])) + recycled_material[P,cup]*(hv_recycling[P]//SUM(recycled_material[P,*])) + recycled_material[Thin,cup]*(hv_recycling[Thin]//SUM(recycled_material[Thin,*])) + recycled_material[New,cup]*(hv_recycling[New]//SUM(recycled_material[New,*]))) * hv_recycling_waste_share[cup]			
other_hv_waste_occurence[ag]	(recycled_material[N,ag]*(hv_recycling[N]//SUM(recycled_material[N,*])) + recycled_material[P,ag]*(hv_recycling[P]//SUM(recycled_material[P,*])) + recycled_material[Thin,ag]*(hv_recycling[Thin]//SUM(recycled_material[Thin,*])) + recycled_material[New,ag]*(hv_recycling[New]//SUM(recycled_material[New,*]))) * hv_recycling_waste_share[ag]			
other_hv_waste_occurence[others]	(recycled_material[N,others]*(hv_recycling[N]//SUM(recycled_material[N,*])) + recycled_material[P,others]*(hv_recycling[P]//SUM(recycled_material[P,*])) + recycled_material[Thin,others]*(hv_recycling[Thin]//SUM(recycled_material[Thin,*])) + recycled_material[New,others]*(hv_recycling[New]//SUM(recycled_material[New,*]))) * hv_recycling_waste_share[others]			
other_waste_occurrence[glass]	(recycled_material[N,glass]*(standard_recycling[N]//SUM(recycled_material[N,*])) + recycled_material[P,glass]*(standard_recycling[P]//SUM(recycled_material[P,*])) + recycled_material[Thin,glass]*(standard_recycling[Thin]//SUM(recycled_material[Thin,*])) + recycled_material[New,glass]*(standard_recycl		ton/year	Represents the annual stream of materials that cannot be recycled in standard recycling, neither in high nor low quality, and needs to be disposed.

	ing[New]//SUM(recycled_material[N,*]))) * downcycling_waste_share[glass]			
other_waste_occurrence[alu]	(recycled_material[N,alu]*(standard_recycling[N]//SUM(recycled_material[N,*])) + recycled_material[P,alu]*(standard_recycling[P]//SUM(recycled_material[P,*])) + recycled_material[Thin,alu]*(standard_recycling[Thin]//SUM(recycled_material[Thin,*])) + recycled_material[New,alu]*(standard_recycling[New]//SUM(recycled_material[New,*]))) * downcycling_waste_share[alu]			
other_waste_occurrence[silicon]	0			
other_waste_occurrence[cup]	(recycled_material[N,cup]*(standard_recycling[N]//SUM(recycled_material[N,*])) + recycled_material[P,cup]*(standard_recycling[P]//SUM(recycled_material[P,*])) + recycled_material[Thin,cup]*(standard_recycling[Thin]//SUM(recycled_material[Thin,*])) + recycled_material[New,cup]*(standard_recycling[New]//SUM(recycled_material[New,*]))) * downcycling_waste_share[cup]			
other_waste_occurrence[ag]	(recycled_material[N,ag]*(standard_recycling[N]//SUM(recycled_material[N,*])) + recycled_material[P,ag]*(standard_recycling[P]//SUM(recycled_material[P,*])) + recycled_material[Thin,ag]*(standard_recycling[Thin]//SUM(recycled_material[Thin,*])) + recycled_material[New,ag]*(standard_recycling[New]//SUM(recycled_material[New,*]))) * downcycling_waste_share[ag]			
other_waste_occurrence[others]	(recycled_material[N,others]*(standard_recycling[N]//SUM(recycled_material[N,*])) + recycled_material[P,others]*(standard_recyclin			

	g[P]//SUM(recycled_material[P,*])) + recycled_material[Thin,others]*(standard_recycling[Thin]//SUM(recycled_material[Thin,*])) + recycled_material[New,others]*(standard_recycling[New]//SUM(recycled_material[New,*]))) * downcycling_waste_share[others]			
P_silicon_recycling[glass]	0		ton/year	The flow represents the annual recovered positively doped silicon from EoL PVs in high-value recycling The successfully recycled material per year is calculated by multiplying the total material in recycling (the specific material and module dimension of the recycled material flow of the material co-flow) with the share of the share of the specific module type that got into hv recycling and the hv recycling efficiency (representing how much of the existing material can be recovered). The unit is ton per year.
P_silicon_recycling[alu]	0			
P_silicon_recycling[silicon]	recycled_material[P,silicon]*(hv_recycling[P]//SUM(recycled_material[P,*])) *hv_recycling_efficiency[silicon]			
P_silicon_recycling[cup]	0			
P_silicon_recycling[ag]	0			
P_silicon_recycling[others]	0			
PV_aging_1[Module_Types]	PV_in_use_1/(PV_lifetime/3)		ton/YEAR	Outflow of PV in use 1 and inflow to PV in use 2, represents aging of the PV modules after one third of their lifetime

				has passed. Unit: Tons per year.
PV_aging_2[Module_Types]	PV_in_use_2/(PV_lifetime/3)		ton/YEAR	Outflow of PV in use 2 and inflow to PV in use 3, represents aging of the PV modules. Unit: Tons per year.
PV_collection[Module_Types]	EoL_PV[Module_Types]*collection_success_rate		ton/YEAR	PV modules that follow the official collection path, arrayed by module type, depending on the panels that reached end of life and the collection success rate. Outflow of EoL PV and inflow to PV available for recycling. Unit
PV_entering_EoL_D3[Module_Types]	PV_in_use_3/(PV_lifetime/3)		ton/YEAR	Outflow of PV in use 3 and inflow to EoL PV, represents entering the End of Life. Unit: Tons per year.
PV_installation_by_material[Module_Types, Materials]	annual_PV_material_installed		ton/YEAR	Same as annual PV material installed, is part of the material co-flow structure and equivalent to annual PV installation in tons.
PV_mat_aging_1[Module_Types, Materials]	PV_material_in_use_1/(PV_lifetime/3)		ton/YEAR	Outflow of PV material in use 1 and inflow to PV material in use 2, represents aging of the PV modules and material after one third of their lifetime has passed. Is part of the material co-flow structure.

				Unit: Tons per year.
PV_mat_aging_2[Module_Types, Materials]	PV_material_in_use_2/(PV_lifetime/3)		ton/YEAR	Outflow of PV material in use 2 and inflow to PV material in use 3, represents aging of the PV modules and material after one third of their lifetime has passed. Is part of the material co-flow structure. Unit: Tons per year.
"PV_mat_entering_EoL_D*"[Module_Types, Materials]	PV_material_in_use_3/(PV_lifetime/3)		ton/YEAR	Outflow of PV material in use 3 and inflow to EoL PV material, , represents entering of EoL of modules and the material they contain. Is part of the material co-flow structure. Unit: Tons per year.
recycled_material[Module_Types, Materials]	PV_mat_available_for_recycling/recycling_processing_time		ton/YEAR	This is the equivalent material flow to the combined flows standard recycling and hv recycling and is needed to calculate the volume of material that can be recovered from both of these recycling methods. Is part of the material co-flow structure. Unit: ton per year.
recycling_capacity_extension	DELAY3(investments_into_capacity//actual_cost_per_additional_capacity_unit, construction_delay)		ton/YEAR	
repowering_D3[Module_Types]	PV_in_use_2*repowering_jump		ton/YEAR	Flow of modules who's use is discontinued before the usual lifetime due to financial or efficiency reasons (repowering). It is draining the PV in use

				2 stock, therefore midlife PVs and it is an inflow to EoL PV. The unit is ton per year.
repowering_mat_D3[Module_Types, Materials]	PV_material_in_use_2*repowering_jump		ton/YEAR	Equivalent to repowering flow but with additional dimensions for material, as part of the material co-flow structure. Unit: ton
repowering_outflow	MW_of_PV_agegroup_2*repowering_jump		Mw/year	Counterpart to repowering flow in module co-flow.
standard_material_recycling[glass]	(recycled_material[N,glass]*(standard_recycling[N]//SUM(recycled_material[N,*])) + recycled_material[P,glass]*(standard_recycling[P]//SUM(recycled_material[P,*])) + recycled_material[Thin,glass]*(standard_recycling[Thin]//SUM(recycled_material[Thin,*])) + recycled_material[New,glass]*(standard_recycling[New]//SUM(recycled_material[N,*]))) * standard_recycling_efficiency[glass]		ton/year	The flow represents the annual recovered materials of high quality in standard recycling. It sumps up each material for all module types. The successfully recycled material per year and module type is calculated by multiplying the total material in recycling (the specific material and module dimension of the recycled material flow of the material co-flow) with the share of the share of the specific module type that got into standard recycling and the standard recycling efficiency (representing how much of the existing material can be recovered in high-quality). The result for each module type is than added up to get the overall recovered volume for each material.
standard_material_recycling[alu]	(recycled_material[N,alu]*(standard_recycling[N]//SUM(recycled_material[N,*])) + recycled_material[P,alu]*(standard_recycling[P]//SUM(recycled_material[P,*])) +			

	recycled_material[Thin,alu]*(standard_recycling[Thin]//SUM(recycled_material[Thin,*])) + recycled_material[New,alu]*(standard_recycling[New]//SUM(recycled_material[New,*]))) * standard_recycling_efficiency[alu]			
standard_material_recycling[silicon]	(recycled_material[N,silicon]*(standard_recycling[N]//SUM(recycled_material[N,*])) + recycled_material[P,silicon]*(standard_recycling[P]//SUM(recycled_material[P,*])) + recycled_material[Thin,silicon]*(standard_recycling[Thin]//SUM(recycled_material[Thin,*])) + recycled_material[New,silicon]*(standard_recycling[New]//SUM(recycled_material[New,*]))) * standard_recycling_efficiency[silicon]			
standard_material_recycling[cup]	(recycled_material[N,cup]*(standard_recycling[N]//SUM(recycled_material[N,*])) + recycled_material[P,cup]*(standard_recycling[P]//SUM(recycled_material[P,*])) + recycled_material[Thin,cup]*(standard_recycling[Thin]//SUM(recycled_material[Thin,*])) + recycled_material[New,cup]*(standard_recycling[New]//SUM(recycled_material[New,*]))) * standard_recycling_efficiency[cup]			
standard_material_recycling[ag]	(recycled_material[N,ag]*(standard_recycling[N]//SUM(recycled_material[N,*])) + recycled_material[P,ag]*(standard_recycling[P]//SUM(recycled_material[P,*])) + recycled_material[Thin,ag]*(standard_recycling[Thin]//SUM(recycled_material[Thin,*])) + recycled_material[New,ag]*(standard_recycling[New]//SUM(recycled_material[New,*]))) * standard_recycling_efficiency[ag]			
standard_material_recycling[others]	(recycled_material[N,others]*(standard_recycling[N]//SUM(recycled_material[N,*])) +			

	recycled_material[P,others]*(standard_recycling[P]//SUM(recycled_material[P,*])) + recycled_material[Thin,others]*(standard_recycling[Thin]//SUM(recycled_material[Thin,*])) + recycled_material[New,others]*(standard_recycling[New]//SUM(recycled_material[New,*]))) * standard_recycling_efficiency[others]			
standard_recycling[Module_Types]	PV_available_for_recycling[Module_Types]*rate_available_for_normal_recycling[Module_Types]		ton/year	
total_PV_entering_EoL[Module_Types, Materials]	"PV_mat_entering_EoL_D*"+repowering_mat_D3		ton/year	
total_yearly_spending_on_hv_recycling	investments_into_capacity+operating_costs		€/year	Calculates the total annual spending on high value recycling (operating costs + investment in capacity). Unit: Euro per year.
yearly_available_resources	MAX(0, financial_resources_after_operating_costs)		€/year	
actual_cost_per_additional_capacity_unit	initial_cost_for_capacity_extension*experience_curve_effect		€/ton	Calculates the costs off adding an additional ton of capacity to high value recycling based on initial costs for the first capacity unit and the experience curve effect, that calculated how much the costs reduce each time the accumulated volume in units of the product doubles (DePamphilis, 2013). The product in this case is capacity. Unit: Euro per ton
additional_projected_PV_installations	PV_goal_gap/installation_time		Mw/year	

aluminum[N]	NAN		dmnl	Share of aluminum included in an average PV module of a module type. The value is imported via excel and changes over time due to technological progress, see supplementary material for more detailed explanation and sources.
aluminum[P]	NAN			
aluminum[Thin]	NAN			
aluminum[New]	NAN			
aluminum_recycling	hv_mterial_recycling[alu]+standard_material_recycling[alu]		ton/year	
aluminum_share	PERCENT(SUM(total_PV_entering_EoL[*,alu])//SUM(total_PV_entering_EoL))		%	
annual_hq_material[Materials]	N_type_recycling + P_silicon_recycling + hv_mterial_recycling + standard_material_recycling		ton/YEAR	Annual stream of high-qulaity recycled material from both recycling streams.
annual_PV_installation_by_module_type[N]	annual_PV_installation_in_MW*n_type_share		Mw/year	Annual installation of PV in MW arrayed by module type based on the market share. Unit: Megawatt per year.
annual_PV_installation_by_module_type[P]	annual_PV_installation_in_MW*p_type_share			
annual_PV_installation_by_module_type[Thin]	annual_PV_installation_in_MW*Thin_Film_share			
annual_PV_installation_by_module_type[New]	annual_PV_installation_in_MW*New_tech			

annual_PV_installation_in_MW	IF TIME < 2024 THEN HIS_PV_installation_in_MW ELSE PV_annual_installation_goal		Mw/year	Annual installation in MW based on historical data until and including 2022, afterwards based on goals. Unit: Megawatt per year.
annual_PV_material_installed[N, glass]	annual_PV_installation_in_tons[N]*glass[N]		ton/year	Annual PV installation in tons arrayed by module and materials calculated by multiplying the annual PV installation in tons, that is arrayed by module with the share of materials also arrayed by module type. The volume of each panel type is therefore further differentiated in different array dimensions that represent the materials the module contains. It is also the input for inflow to the stock PV in use 1, it represents the volume of material that is installed each year. Unit: Tons per Year.
annual_PV_material_installed[N, alu]	annual_PV_installation_in_tons[N]*aluminum[N]			
annual_PV_material_installed[N, silicon]	annual_PV_installation_in_tons[N]*silicon[N]			
annual_PV_material_installed[N, cup]	annual_PV_installation_in_tons[N]*copper[N]			
annual_PV_material_installed[N, ag]	annual_PV_installation_in_tons[N]*silver[N]			
annual_PV_material_installed[N, others]	annual_PV_installation_in_tons[N]*other_materials[N]			
annual_PV_material_installed[P, glass]	annual_PV_installation_in_tons[P]*glass[P]			

annual_PV_material_installed[P, alu]	annual_PV_installation_in_tons[P]*aluminum[P]			
annual_PV_material_installed[P, silicon]	annual_PV_installation_in_tons[P]*silicon[P]			
annual_PV_material_installed[P, cup]	annual_PV_installation_in_tons[P]*copper[P]			
annual_PV_material_installed[P, ag]	annual_PV_installation_in_tons[P]*silver[P]			
annual_PV_material_installed[P, others]	annual_PV_installation_in_tons[P]*other_materials[P]			
annual_PV_material_installed[Thin, glass]	annual_PV_installation_in_tons[Thin]*glass[Thin]			
annual_PV_material_installed[Thin, alu]	annual_PV_installation_in_tons[Thin]*aluminum[Thin]			
annual_PV_material_installed[Thin, silicon]	annual_PV_installation_in_tons[Thin]*silicon[Thin]			
annual_PV_material_installed[Thin, cup]	annual_PV_installation_in_tons[Thin]*copper[Thin]			
annual_PV_material_installed[Thin, ag]	annual_PV_installation_in_tons[Thin]*silver[Thin]			
annual_PV_material_installed[Thin, others]	other_materials[Thin]*annual_PV_installation_in_tons[Thin]			
annual_PV_material_installed[New, glass]	annual_PV_installation_in_tons[New]*glass[New]			
annual_PV_material_installed[New, alu]	annual_PV_installation_in_tons[New]*aluminum[New]			
annual_PV_material_installed[New, silicon]	annual_PV_installation_in_tons[New]*silicon[New]			

annual_PV_material_installed[New, cup]	copper[New]*annual_PV_installation_in_tons[New]			
annual_PV_material_installed[New, ag]	annual_PV_installation_in_tons[New]*silver[New]			
annual_PV_material_installed[New, others]	annual_PV_installation_in_tons[New]*other_materials[New]			
capacity_doubling_count	IF High_value_recycling_capacity >= 1 THEN LN(High_value_recycling_capacity)/LN(2) ELSE 0		dmnl	The capacity doubling count is an input to the learning curve effect. It counts the amount of times the high value recycling capacity has doubled by using the base two logarithm of it.
capacity_gap	MAX(0, required_capacity_forecast-High_value_recycling_capacity)		ton	Gap between capacity requirement forecast and current capacity. Unit: ton.
collection_success_rate	GRAPH(TIME) Points: (2015.00, 0.0000), (2015.40, 0.2307), (2015.80, 0.2601), (2016.20, 0.2882), (2016.60, 0.3152), (2017.00, 0.3411), (2017.40, 0.3659), (2017.80, 0.3897), (2018.20, 0.4125), (2018.60, 0.4343), (2019.00, 0.4553), (2019.40, 0.4753), (2019.80, 0.4946), (2020.20, 0.5130), (2020.60, 0.5307), (2021.00, 0.5476), (2021.40, 0.5638), (2021.80, 0.5794), (2022.20, 0.5943), (2022.60, 0.6086), (2023.00, 0.6223), (2023.40, 0.6354), (2023.80, 0.6480), (2024.20, 0.6601), (2024.60, 0.6717), (2025.00, 0.6827), (2025.40, 0.6934), (2025.80, 0.7036), (2026.20, 0.7133), (2026.60, 0.7227), (2027.00, 0.7316), (2027.40, 0.7402), (2027.80, 0.7485), (2028.20, 0.7564), (2028.60, 0.7639),		dmnl/year	Share of EoL modules that are collected via official collection points per year. Collection efforts started in 2015. Collection success is assumed to have logarithmic growth until they reach 85% in 2035. The reported collection success from 2015 to 2022 is fluctuating, they report a goal of 85% collection rate. In the model, the assumption is that they will need until 2035 to build up the infrastructure and awareness to reach this goal. Since no evidence is found so far, that module types are handled differently in the collection process, the same collection rate is assumed for all module types. Unit: Dimensionless per year.

	(2029.00, 0.7712), (2029.40, 0.7781), (2029.80, 0.7848), (2030.20, 0.7912), (2030.60, 0.7973), (2031.00, 0.8032), (2031.40, 0.8088), (2031.80, 0.8142), (2032.20, 0.8194), (2032.60, 0.8243), (2033.00, 0.8291), (2033.40, 0.8336), (2033.80, 0.8380), (2034.20, 0.8422), (2034.60, 0.8462), (2035.00, 0.8500)			
combined_annual_silicon_recycling	SUM(P_silicon_recycling)+SUM(N_type_recycling)		ton/year	Sums up the negatively and positively doped annually recovered silicon volumes. Unit: Ton per year.
construction_delay	2		year	The time it takes to build new high-value recycling capacity is assumed to be 3 years. It is input to recycling capacity extension and required capacity forecast. The unit is year.
control_variable_1	SUM("PV_mat_entering_EoL_D*")-SUM(PV_entering_EoL_D3)		ton/year	Control variable shows difference in volume of module and material co-flow at the entering EoL stage, should be 0.
control_variable_2	aluminum_share + copper_share + glass_share + other_material_share + silicon_share + silver_share		%	Control variable should be 0 if no PV modules have entered EoL yet, or 100 if they have. If not, this suggest a mistake in modeling the material array.
control_variable_3	N_Type_share_in_EoL + P_Type_share_in_EoL + Thin_film_share_in_EoL		%	Control variable should be 0 if no PV modules have entered EoL yet, or 100 if they have. If not, this suggest a mistake in modeling the module array.

control_variable_4	(SUM(standard_recycling) + SUM(hv_recycling)) - SUM(recycled_material)		ton/year	Control variable shows difference in volume of module and material co-flow at the entering recycling, should be 0.
control_variable_summary	IF (control_variable_1 = 0 AND control_variable_4 =0 AND module_type_control_variable = 1) AND ((TIME > 2005 AND control_variable_2 =100 AND control_variable_3 =100) OR TIME <= 2005) THEN 1 ELSE 0		dmnl	Control variable summary should be 1, otherwise at least 1 control variable shows a value suggesting a fault in material flow consistency.
copper[N]	0.01		dmnl	Share of copper in an average module type, it is assumed to be approximately stable, since it is mostly present in the junction box.
copper[P]	0.01			
copper[Thin]	0.01			
copper[New]	0			
copper_share	PERCENT(SUM(total_PV_entering_EoL[*,cup])//SUM(total_PV_entering_EoL))		%	
cumulative_hq_material[Materials]	N_type_silicon + P_Type_silicon + hv_other_materials + standard_rec_materials		ton	
downcycling_efficiency[glass]	0.98		dmnl	Represents the share of each material that can be recovered in high quality during a high-value recycling process. Values are derived from different recycling projects, see paper for further explanation and sources. For simplification reasons, the value is assumed to be stable and do not differ between module types. Unit: Dimensionless

downcycling_efficiency[alu]	0			
downcycling_efficiency[silicon]	0.9			
downcycling_efficiency[cup]	0			
downcycling_efficiency[ag]	0			
downcycling_efficiency[others]	0			
downcycling_waste_share[Materials]	1-downcycling_efficiency-standard_recycling_efficiency		dmnl	
early_investment	IF TIME >= 2018 AND TIME < investment_stop_time THEN yearly_investment_rate ELSE 0		€/year	
experience_curve_effect	(1-learning_effect_strength)^capacity_doubling_count		dmnl	"In its simplest form, the experience curve (EC) represents the relationship between cost and volume when accumulated volume has doubled. The slope of the experience curve when accumulated volume has doubled equals 2^alpha. This formula implies that, each time the accumulated volume in units of the product doubles, costs drop by 1-2^alpha." DePamphilis, 2013, p. 1 This variable applies the learning curve effect and represents the share of the initial costs that the next capacity unit costs at any given time. Unit: dimensionless
fee_per_ton	50 {Standrad 24 High: 50}		€/ton	
financial_resources_after_operating_costs	self_financing-operating_costs		€/year	

fixed_costs	IF TIME > 2018 THEN 20000 ELSE 0		€/year	Fixed costs are yearly costs that are independent of the size of the operation, e.g. certain administrative costs. Fixed costs start occurring when the operation starts with the start of PAYP. The value is an assumption and subject to scenario development.
France_installation_goals_high	NAN		GW	https://www.ecologie.gouv.fr/sites/default/files/documents/23242_Strategie-energie-climat_def2_0.pdf p.19
France_installation_goals_low	NAN		GW	Old goals set in 2008 https://www.pv-magazine.com/2023/08/08/france-aims-for-48-1-gw-of-solar-by-2030-140-gw-by-2050/
glass[N]	NAN		dmnl	Share of glass included in an average PV module of a module type. The value is imported via excel and changes over time due to technological progress, see supplementary material for more detailed explanation and sources.
glass[P]	NAN			
glass[Thin]	NAN			
glass[New]	NAN			
glass_share	PERCENT(SUM(total_PV_entering_EoL [*,glass])//SUM(total_PV_entering_EoL))		%	
Goal_SWITCH	1		dmnl	
high_value_recycling_share	PERCENT(SUM(hv_recycling)//SUM(total_PV_entering_EoL))		%	Sum of yearly recycling, summarizing both high-value and standard recycling.

				Unit: Ton per Year.
HIS_PV_installation_in_MW	NAN		Mw/year	vor 2008 Schätzung auf Grundlage des Wissens das vor 2008 insgesamt nur 7MW installiert wurden 2008 bis 2022: Bilan électrique 2022 rapport complet (im Report selbst nur als Grafik, Zahlen von Wikipedia: https://fr.wikipedia.org/wiki/%C3%89nergie_solaire_en_France dort ist allerdings Bilan als Quelle angegeben)
HIS_SOREN_collection_rate	NAN		ton/year	The variable imports the annual collection of used PV in tons from Excel. The collection is conducted by the French producer Responsibility organization SOREN and includes all collected EoL PVs,including from oversea departements (SOREN 2023). The variable is used as reference mode. Unit: Ton per year
hv_recycling_efficiency[glass]	0.85		dmnl	Represents the share of each material that can be recovered in high quality during a high-value recycling process. Values are derived from different recycling projects, see paper for further explanation and sources. For simplification reasons, the value is assumed to be stable and do not differ between module types. Unit: Dimensionless

hv_recycling_efficiency[alu]	0.98			
hv_recycling_efficiency[silicon]	0.95			
hv_recycling_efficiency[cup]	0.85			
hv_recycling_efficiency[ag]	0.8			
hv_recycling_efficiency[others]	0			
hv_recycling_waste_share[Materials]	1-hv_recycling_efficiency		dmnl	Represents the share of each material that cannot be recovered during high-value recycling and therefore needs to be disposed. Calculated by subtracting the recoverable share. Unit: Dimensionless
hypothetical_maximum_recycling_value[Module_Types, Materials]	cumulative_exported_PV_mat+cumulative_recycled_material		ton	Hypothetical maximum volume (cumulative) of material that could be recovered. This maximum would imply a 100% collection rate and no loss of material during the recycling process. Unit: ton.
hypothetical_maximum_recycling_value_per_year[Module_Types, Materials]	material_export+recycled_material		ton/YEAR	Hypothetical maximum annual volume of material that could be recovered. This maximum would imply a 100% collection rate and no loss of material during the recycling process. Unit: ton per year.
initial_cost_for_capacity_extension	20000 {50000}		€/ton	Initial costs for the first capacity unit of high-value recycling, this includes research and development. The value is an assumption and subject to scenario development.

installation_time	1		year	
investment_stop_time	2021 {3 Years = 2021 7 Years = 2025}		year	
IRENA_early_loss_cumulative_waste_vol	NAN		ton	Imports the cumulative PV waste volume according to the early loss scenario of IRENA (IRENA: Weckednet al. 2016). Unit: ton
IRENA_regular_cumulative_waste_vol	NAN		ton	Imports the cumulative PV waste volume according to the regular loss scenario of IRENA (IRENA: Weckednet al. 2016). Unit: ton
learning_effect_strength	0.21		dmnl	The learning effect strength represents the reduction in costs that occurs every time the capacity doubles. The value is an assumption.
module_type_control_variable	p_type_share+n_type_share+Thin_Film_share+New_tech		dmnl	Control variable, always needs to be one. Sums together the shares of different modules types, check data imput for module types shares if not one.
MW_to_GW_converter	1000		MW/GW	One gigawatt corresponds to 1000 megawatt. Unit: Megawatt per Gigawatt
n_type_share	(1-Thin_Film_share)*"N-type_share_of_c_Si_modules"		dmnl	Share of N-type c-Si-Silicon modules in the PV market, calculated by subtracting the share of thin film modules and multiplying the left over share (the share of c-Si-modules) with the share of N-Type modules within the c-Si-market. N-Type modules include modules with

				mono or polycrystalline silicon that are doped with phosphorus. Used to be the minority but is now the standard technology.
N_Type_share_in_EoL	PERCENT(SUM(total_PV_entering_EoL[N,*])//SUM(total_PV_entering_EoL))		%	
"N-type_share_of_c_Si_modules"	NAN		dmnl	Imports market share of N-type modules within the market of c-Si-modules. See supplementary material for sources.
New_tech	0		dmnl	Share of a potential new PV technology, included in the model for scenario building in future iterations of the model. Share is zero for this iteration of the model building process.
operating_costs	High_value_recycling_capacity*variable_operating_cost_per_capacity_unit+fixed_costs		€/year	Operating costs per year, including fixed and variable costs. Unit: Euro per year.
other_material_share	PERCENT(SUM(total_PV_entering_EoL [*,others])//SUM(total_PV_entering_EoL))		%	
other_materials[Module_Types]	1-aluminum-glass-copper-silicon-silver		dmnl	
p_type_share	(1-Thin_Film_share)*(1-"N-type_share_of_c_Si_modules")		dmnl	Share of P-type c-Si-Silicon modules in the PV market, calculated by subtracting the share of thin film modules and the share of N-type modules. P-Type modules include modules with mono or polycrystalline silicon that is doped with boron or gallium. It used to be the dominant technology in the past, but is fading out.

P_Type_share_in_EoL	PERCENT(SUM(total_PV_entering_EoL[P,*])//SUM(total_PV_entering_EoL))		%	
panel_to_power_ratio	NAN		ton/MW	Exponential curve fit of projection of PV panel weight-to-power ratio (t/MW) by IRENA: Weckend et al. 2016 p.27. The curve represents the decrease in material needed per megawatt of potential production by PV. Unit: Tons per Megawatt
Priority[N]	10		dmnl	Priority is an input to the allocation function used in the flow hv recycling. Arrays with higher values for priority are Priority, and therefore higher values, are given to both c-Si-module types since they have the largest market share and therefore high-value recycling is focusing on them. No differentiation is given between N and P-Type modules since currently recyclers or collection organizers do not sort between different c-Si types.
Priority[P]	10			
Priority[Thin]	2			
Priority[New]	0			
PV_annual_installation_goal	additional_projected_PV_installations+accounting_PV_MW_wear_out+repowering_outflow		Mw/year	Installation goals are calculated in a way to increase capacity if goals are above current capacity and replace PVs that are entering EoL regularly or through repowering. The variable only has

				influence after 2022, before that historical data is used.
PV_goal_gap	(IF Goal_SWITCH = 1 THEN France_installation_goals_high-Total_PV_in_GW ELSE France_installation_goals_low-Total_PV_in_GW) *MW_to_GW_converter		MW	Gap between currently installed PV capacity and the goal for the year. Unit: Megawatt.
PV_lifetime	27		years	PV lifetime is typically reported to be between 25 and 30 years, based on that 27 years are chosen.
rate_available_for_normal_recycling[Module_Types]	1-(hv_recycling//PV_available_for_recycling)		dmnl/year	Share of PVs that cannot be recycled via high-value recycling and therefore needs to be recycled via standard recycling. The share is different for each module type array. It is calculated via the total available PV for recycling and the number of PVs recycled via high-value recycling. Unit: dimensionless per year.
recycling_payment	SUM(hv_recycling)*fee_per_ton		€/year	
recycling_processing_time	1		year	
repowering_jump	STEP(repowering_share, 2026)		dmnl/year	
repowering_share	0.005 {0 = No Repowering, 0.005= Low repowering Scenario 0.05 = High repowring scenario}		dmnl/year	
required_capacity_forecast	FORCST(SUM(PV_available_for_recycling), 3, construction_delay)		ton	Required capacity forecast is used as an input to calculate the capacity gap for high value recycling capacity. A forecast function is used that takes into account

				the last three years of PV available for recycling (the sum of all module types) and extrapolates a trend from there for the next three years. This is done since the construction time for new recycling capacity is three years.
self_financing	recycling_payment+early_investment		€/year	
silicon[N]	0.05		dmnl	Share of silicon included in an average PV module of a module type. The value is imported via excel and changes over time due to technological progress, see supplementary material for more detailed explanation and sources.
silicon[P]	0.05			
silicon[Thin]	0			
silicon[New]	0			
silicon_share	PERCENT(SUM(total_PV_entering_EoL [*,silicon])//SUM(total_PV_entering_EoL))		%	
silver[N]	NAN		dmnl	Share of silver included in an average PV module of a module type. The value is imported via excel and changes over time due to technological progress, see supplementary material for more detailed explanation and sources.
silver[P]	NAN			
silver[Thin]	NAN			
silver[New]	NAN			
silver_share	PERCENT(SUM(total_PV_entering_EoL [*,ag])//SUM(total_PV_entering_EoL))		%	

SOREN_waste_stream_projection	NAN		ton/year	Imports the annual waste stream projection by Soren, includes all EoL PVs in France (Sorenewable presentation 2023). The variable is used as reference mode. Unit: Ton per year
Spread	0 {If priority_spread is 0 then higher priority indices are supplied first. When it is positive higher priority indices will get a larger share or their target, but lower priority indices may also receive a portion of their target.}		dmnl	Spread is the input to priority spread in the allocation function used in the flow hv recycling. The spread is 0, this means higher priority indices are supplied first. If the spread has a positive value, higher priority indices will get a larger share or their target, but lower priority indices may also receive a portion of their target.
standard_recycling_efficiency[glass]	0		dmnl	Represents the share of each material that can be recovered in high quality during a standard recycling process. Values are derived from different recycling projects, see paper for further explanation and sources. For simplification reasons, the value is assumed to be stable and do not differ between module types. Unit: Dimensionless
standard_recycling_efficiency[alu]	0.98			
standard_recycling_efficiency[silicon]	0			
standard_recycling_efficiency[cup]	0.45			

standard_recycling_efficiency[ag]	0			
standard_recycling_efficiency[others]	0			
Thin_Film_share	NAN		dmnl	Imports market share of thin-film modules (e.g. CIGS, CdTe) from Excel-File. See supplementary material for sources. Until 2023 historical data is used, afterwards a stable share of 2.5% is assumed.
Thin_film_share_in_EoL	PERCENT(SUM(total_PV_entering_EoL[Thin,*])//SUM(total_PV_entering_EoL))		%	
time_to_invest	1		year	
Total_PV_in_GW	Total_PV_in_MW/MW_to_GW_converter		GW	
Total_PV_in_MW	MW_of_PV_agegroup_1+MW_of_PV_agegroup_2+MW_of_PV_agegroup_3		MW	Total power capacity of currently installed PV in France in Megawatt. Unit: Megawatt
total_spending_per_ton_of_hq_recycled_PV	total_sepnding_on_hq_recycling// SUM(cumulative_high_value_recycled_PVs[*])		€/ton	
variable_operating_cost_per_capacity_unit	5		€/ton/year	Cost per ton per year of operation of high-value recycling, this includes energy costs, labour, maintenance etc. The value is an assumption and subject to scenario development. Unit: Euro per ton per year.
yearly_investment_rate	10000000 {Low value: 6000000 High value 10000000}		€/year	

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