Flows of engineered nanomaterials through the recycling system in Switzerland

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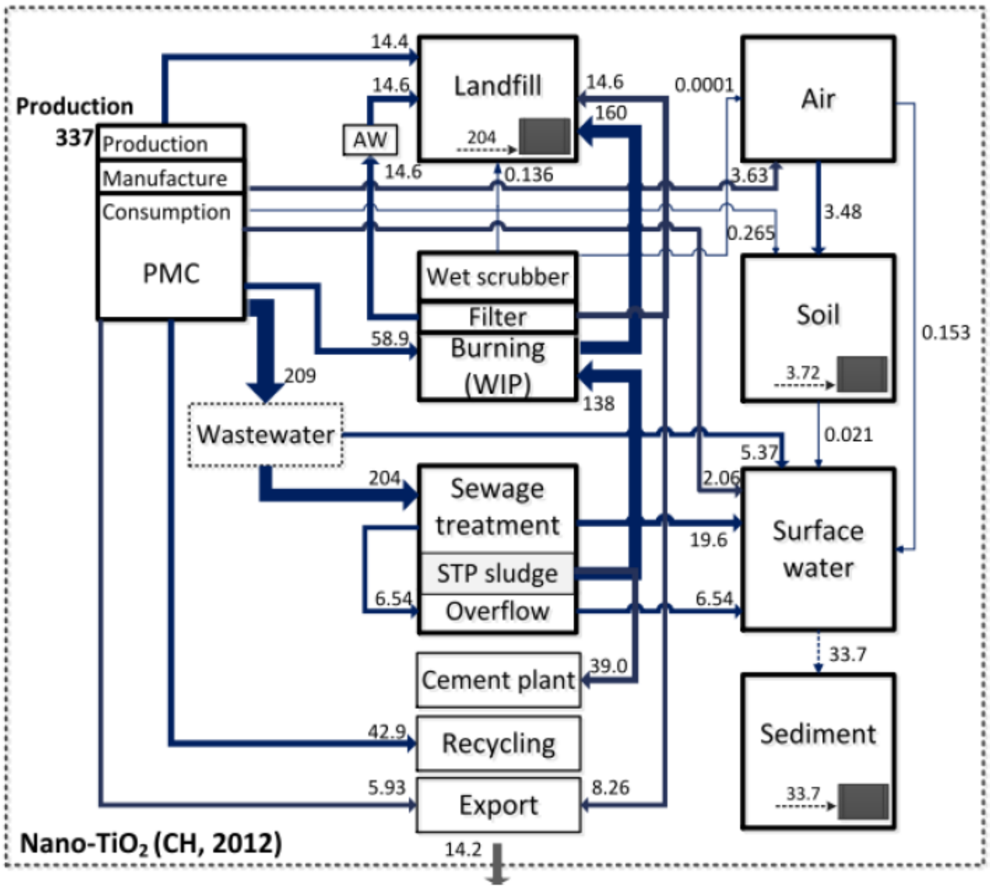
I. Background and goal

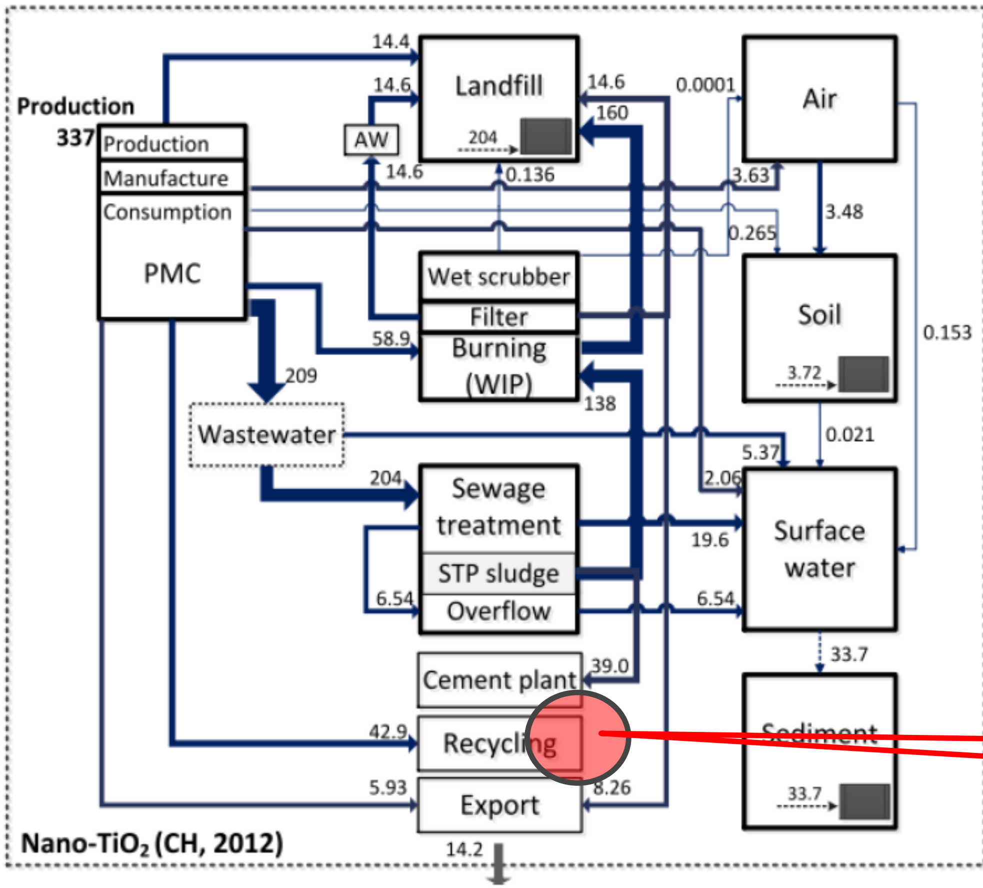


- Sun et al. (2014) estimated the ENM mass flows in Switzerland and the European Union
  - Pigment-TiO_2
  - Nano-TiO_2
  - Nano-Ag
  - Nano-ZnO
  - CNT
  - Fullerenes

T. Y. Sun, F. Gottschalk, K. Hungerbuhler, B. Nowack, Comprehensive probabilistic modelling of environmental emissions of engineered nanomaterials. *Environmental Pollution* 185, 69 (2014).

I. Background and goal

ETH Eidgenössische Technische Hochschule Zürich — EMPA Materials Science & Technology



- Goal: Model and quantify the outflows from the recycling system in Switzerland.
- ENMs considered:
  - Nano-Ag
  - Nano-TiO_2
  - Nano-ZnO
  - CNT

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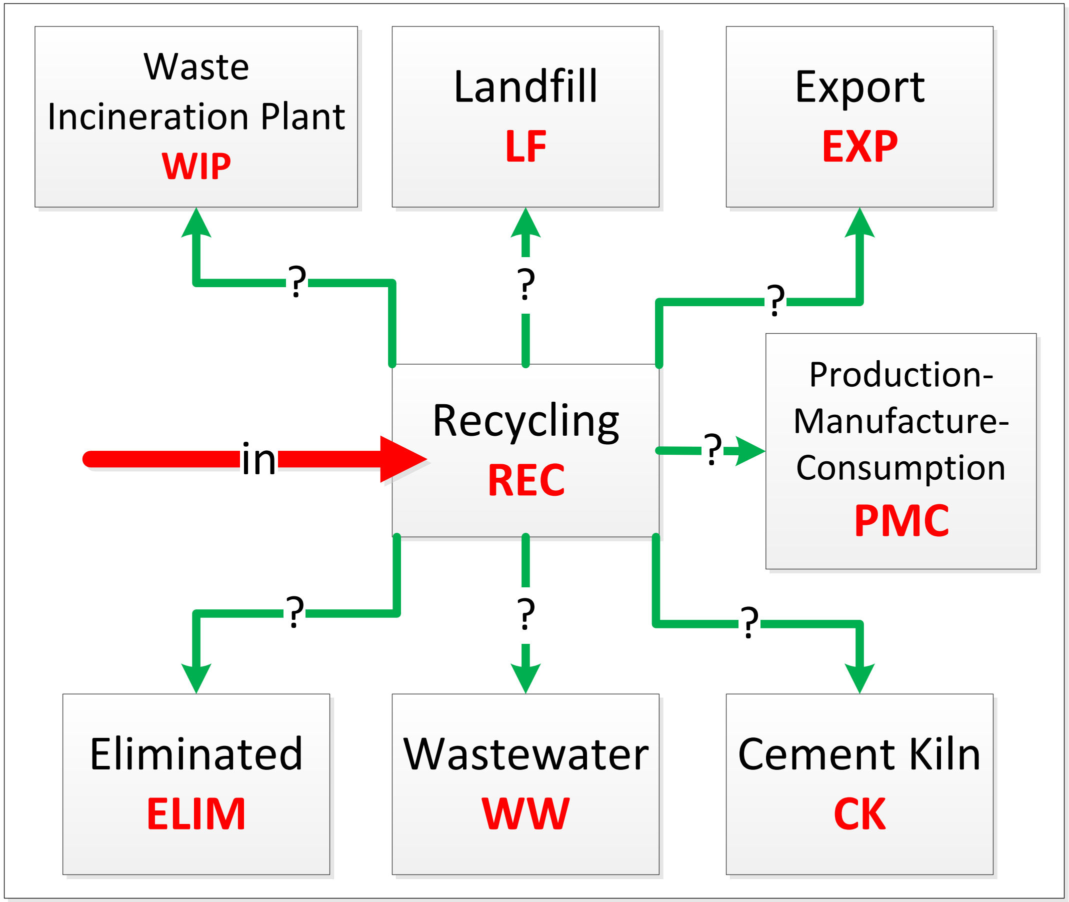
II. Method

1. a) System definition.



II. Method

1. b) Input information analysis

- 33 consumer products categories analyzed using public inventories






II. Method

1. b) Input information analysis

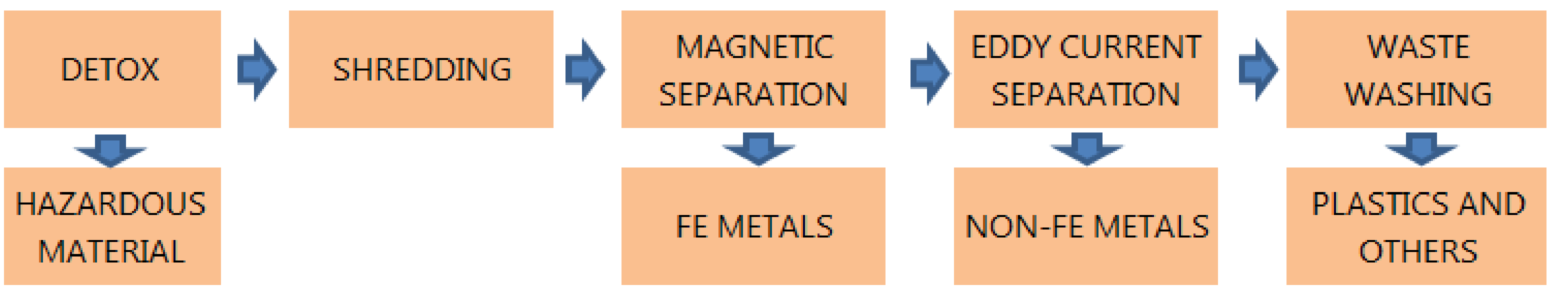
- Nano-mass input to recycling (Tons per year in 2012), based on Sun et al. (2014)

	Percentile 15	Mode	Percentile 85
Nano-TiO_2	30	43	79
Nano-ZnO	3	5	18
CNT	2	3	5
Nano-Ag	0.3	0.4	0.5

II. Method

2. Chacterization of the recycling system using flow diagrams

E-waste recycling process (example)



Sources: Goodship and Stevels (2012) and info available in Internet, among others.

II. Method

3. Calculate the transfer vectors

$$For\ each\ product\ category\ i, determine$$

$$(TC_{WIP}, TC_{LF}, TC_{EXP}, TC_{PMC}, TC_{CK}, TC_{WW}, TC_{ELIM})$$

$$such\ that\ 0 \leq TC_x \leq 1\ and \sum TC_x = 1$$

II. Method

3. Calculate the transfer vectors.

	Step 1	*Step 2*	*Step 3*	*Step 4*	*Result*
Consumer electronics	Products with ENM in plastics	(TC_{WIP}, TC_{EXP}) (0.50, 0.50) ×	0.70 =	(0.35,0.35) +	= (0.45,0.55)
	Products with ENM in batteries	(TC_{WIP}, TC_{EXP}) (0.33, 0.66) ×	0.30 =	(0.10,0.20)	
	Split into product subcategories	*Assess TCs by subcategories*	*Multiply by mass distribution*	*Sum the weighted vectors*	*Category transfer vector*

II. Method

4. Stochastic flow calculation

- Probabilistic approach of MFA to incorporate uncertainty based on Gottschalk et al. (2010) → simulation using Monte Carlo-Markov Chain
- TC's used to define triangular distributions
  - Mode = TC point value
  - Lower bound = 50% of the TC
  - Upper bound = 150% of the TC
- Distributions simulation using 100,000 random values

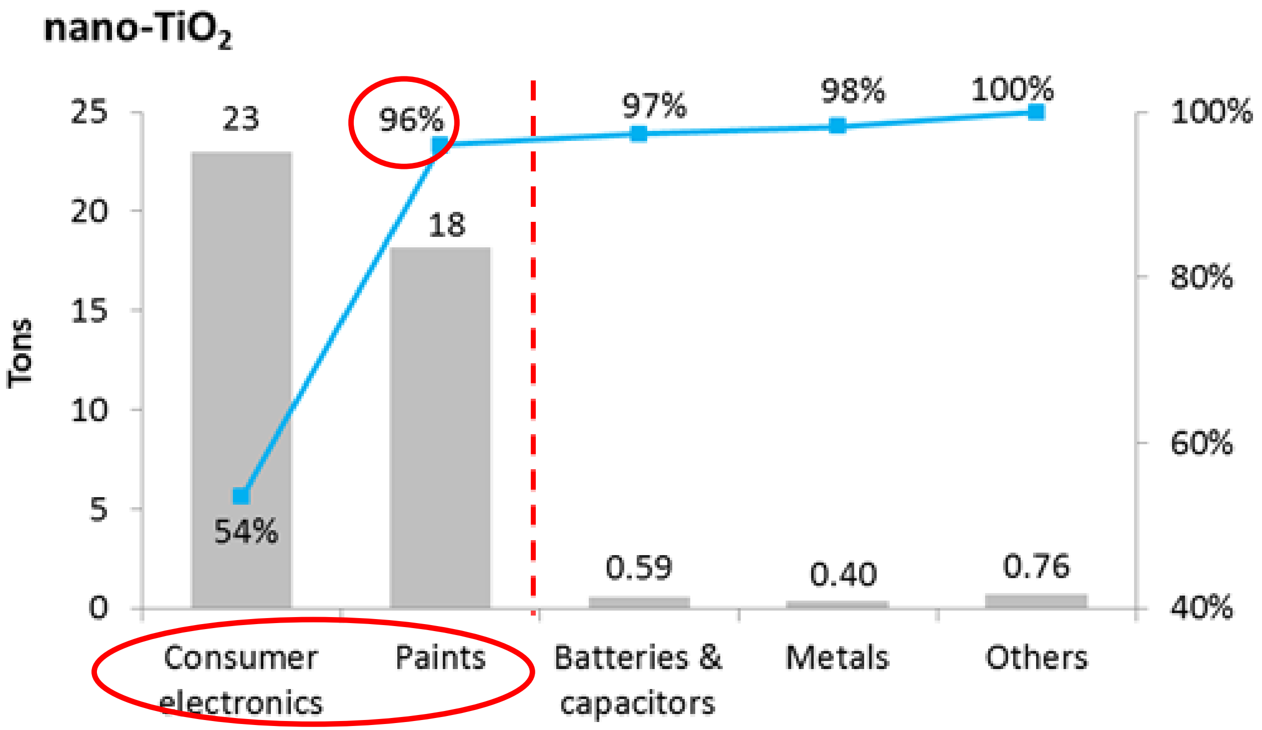
F. Gottschalk, R. W. Scholz, B. Nowack, Probabilistic material flow modeling for assessing the environmental exposure to compounds: Methodology and an application to engineered nano-TiO2 particles. *Environmental Modelling & Software* 25, 320 (2010).

Model assumptions

- Mass-based approach
- ENM characteristics (size distribution, shape…) have no influence on final fate
- ENM transformations considered: only elimination
- Static model (all flows occur in one year)

III. Results (nano-TiO_2 case)

1. Only «relevant» product categories selected (relevancy measured by total nano-mass transferred to recycling; at least ≥95%)



III. Results (nano-TiO_2 case)

2. Product types analysis
   a) Composition
   b) Material fraction with ENM

Consumer electronics





Paints

III. Results (nano-TiO_2 case)

3. Fate of the material fractions with ENM within the Swiss recycling system.

Material fraction	Associated recycling process	Fate
Ceramics	E-waste	WIP
Filter components	E-waste, cooling devices	WIP
Li-ion batteries	E-waste	Exported
Plastics	E-waste, cooling devices	WIP, Exported

Sources: waste management statistics and regulations; discussions with experts.

III. Results (nano-TiO_2 case)

4. Transfer vector assessment for the Consumer Electronics subcategories.

Product Category	Material fraction	Distribu-tion (%)	Transfer Coefficients (TCs)						
			WIP	LF	EXP	PMC	CK	WW	ELIM
Consumer electronics	Ceramics	74	0.96	-	-	-	-	0.04	-
	Plastics	22	0.48	-	0.48	-	-	0.04	-
	Filter components	4	1.00	-	-	-	-	-	-
	TOTAL	100	0.85	-	0.11	-	-	0.04	-

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II. Method

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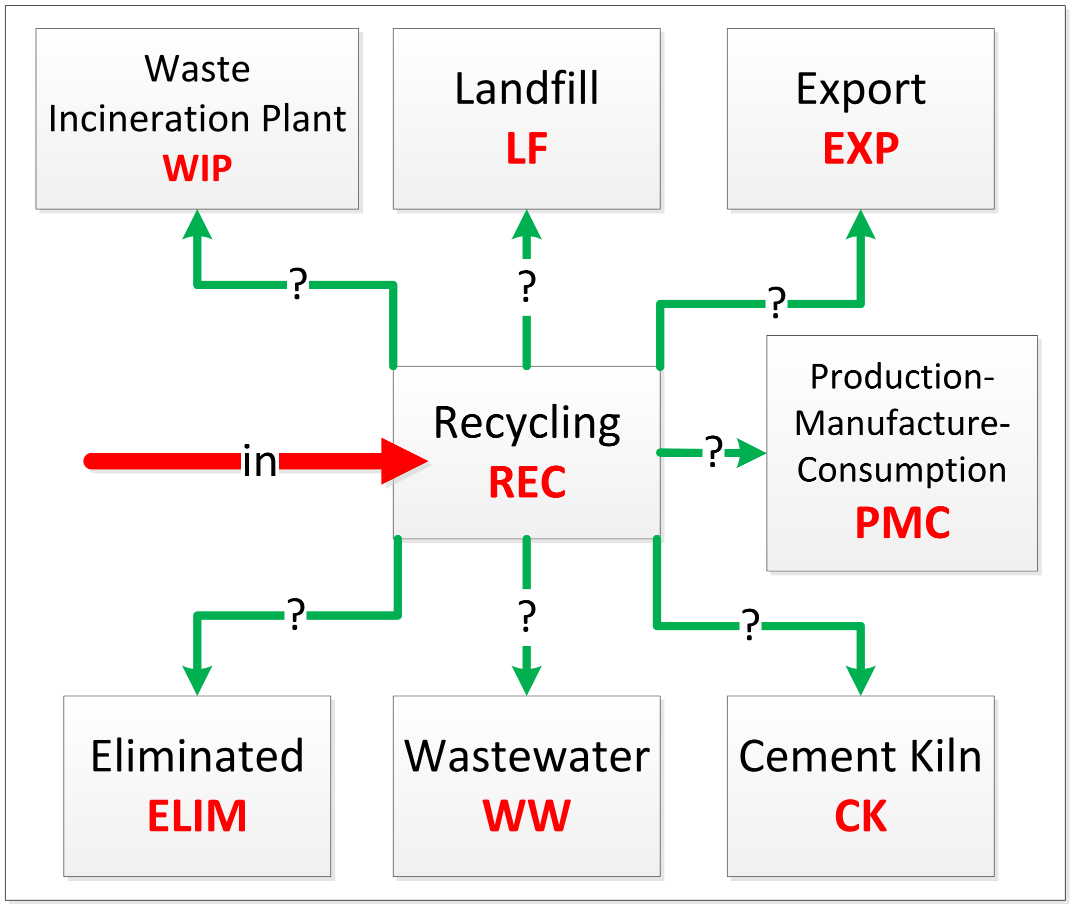

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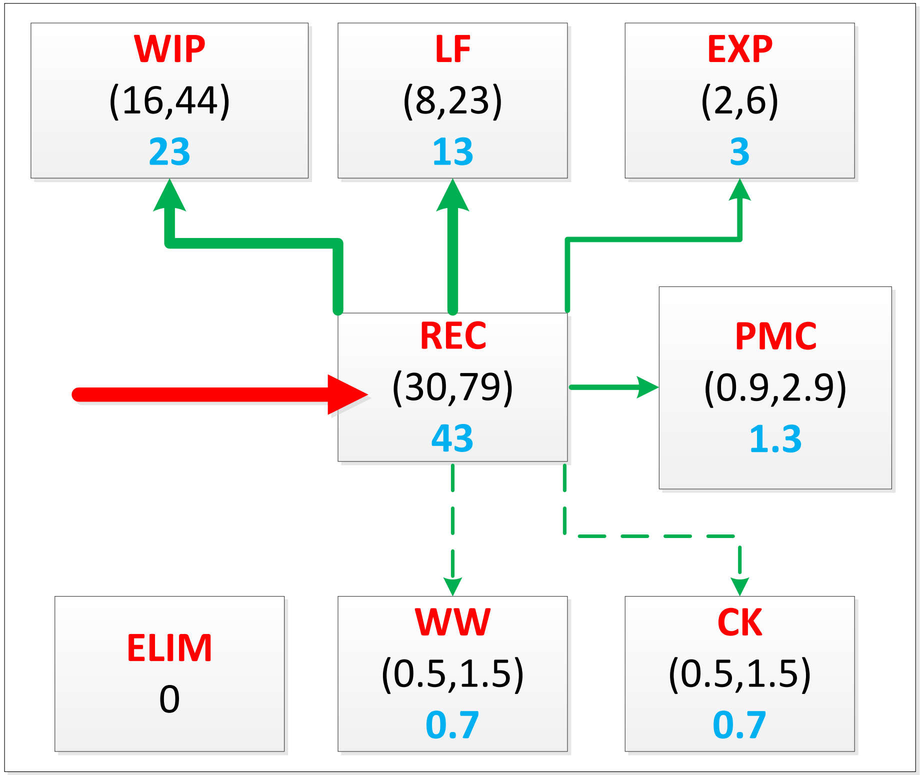
III. Results (nano-TiO_2 case)

5. Transfer vectors for the product categories with nano-TiO_2:
   - Final input for the simulation of the probability distributions.

ENM	Product category	Transfer Coefficients (TCs)						
		WIP	LF	EXP	PMC	CK	WW	ELIM
TiO_2	Consumer electronics	0.85	-	0.11	-	-	0.04	-
	Paint	0.20	0.68	-	0.08	0.04	-	-

III. Results (nano-TiO_2 case)

6. ENM probabilistic flows in 2012 (tons/year). Mode values **(in blue)** and percentiles 15th and 85th.



Note: Thickness and pattern of the green arrows reflect the magnitude regarding the overall flow.

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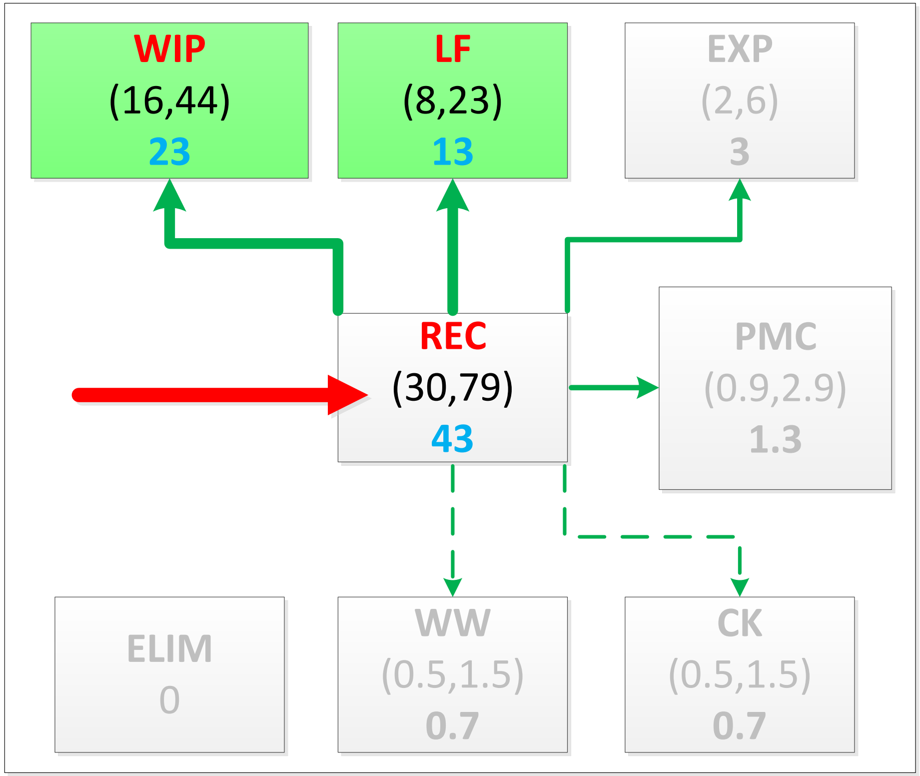

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- Waste Incineration Plant (WIP): plastics, painted wood, ceramics
- Landfill (LF) : mineral material with paint (e.g. gypsum, plaster)

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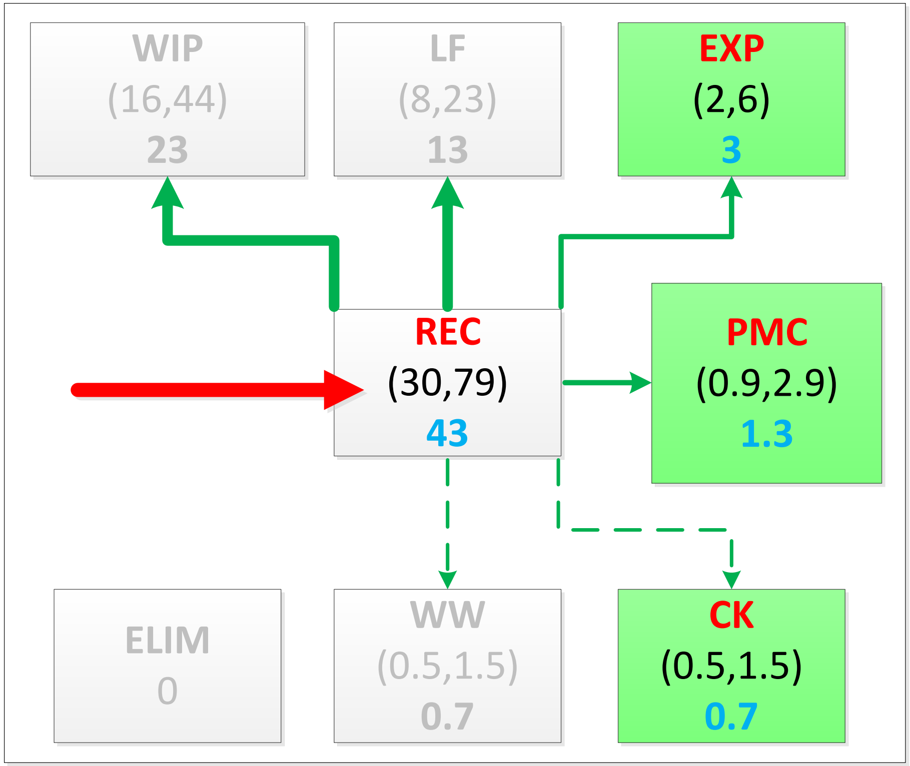

- Exported (EXP): plastics
- Production-Manufacture-Consumption (PMC): demolished concrete
- Cement Kiln (CK): mineral residues or wood with paint

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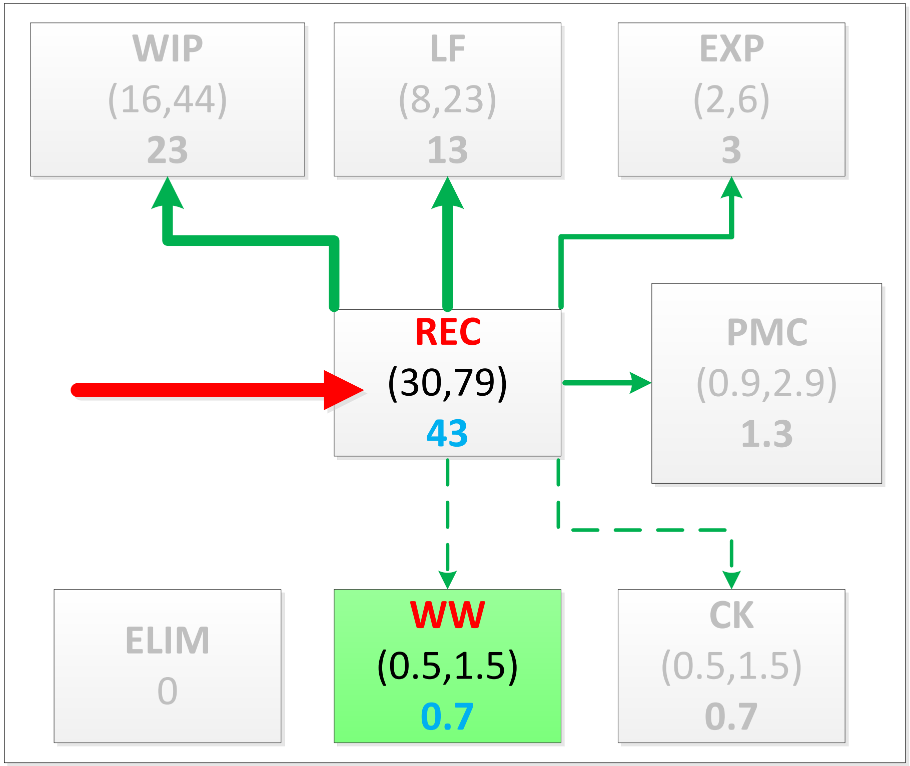

- Waste water (WW): releases during washing processes applied during recycling.

Note: Thickness and pattern of the green arrows reflect the magnitude regarding the overall flow.

III. General Results

Main and secondary fates of ENM after recycling (outflows (mode values) in 2012 tons). In orange letters the associated material fraction with ENM.

ENM	ZnO	Ag	CNT
Main fate	Landfills (3t) Mineral waste	WIP (0.2t) Plastics, filters, wood	Exported (2.4t) Batteries, chips, PCBs
Secondary fates	WIP (1t) Wood Cement+Concrete production (<1t) Mineral waste	Exported (0.06t) Plastics and textiles Eliminated (0.06t) Fe-metal Waste water (0.04t) Landfill (<0.01t) Mineral waste Cement+Concrete production (<0.01t) Mineral waste	Eliminated (<1t) Non-fe metals Incinerated (<1t) Nanocomposites Car composites re-used (<1t)

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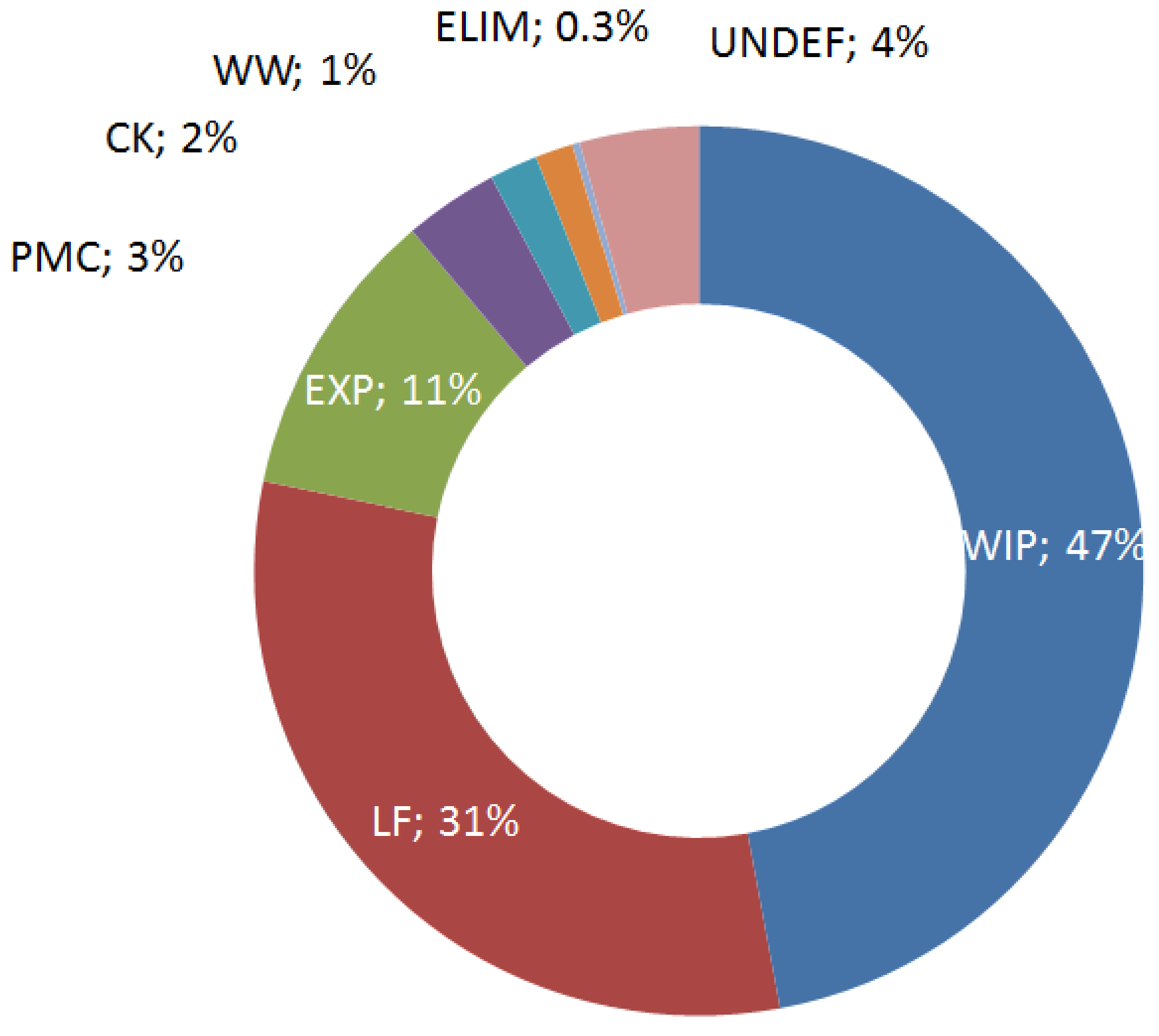
III. Total ENM outflow distribution (all ENMs)



IV. Conclusions

- Main flows to waste incineration, landfills or exported.
- No significant dissipation of ENM to new products (only to very small extent into plastics, concrete and cement).
- ENM risk assessment during recycling should focus on occupational exposure and release to the environment.
- Main uncertainties
  - ENM mass distribution between product subcategories
  - ENM release kinetics → Product knowledge

Thanks!

MAIN REFERENCE

- **Caballero-Guzman, A., T. Y. Sun and B. Nowack (2015)**. "Flows of engineered nanomaterials thorugh the recycling process in Switzerland." Waste Management. 36: 33-45. DOI: **10.1016/j.wasman.2014.11.006**

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CONTACT INFORMATION

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