

# **Prospective dynamic and probabilistic material flow analysis of graphene-based materials in Europe from 2004 to 2030**

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## **Supporting Information 2**

Number of pages in supporting information: 7

Number of figures: 7

Number of tables: 5

# 1 Details on the method

## 1.1 Conceptual process diagram

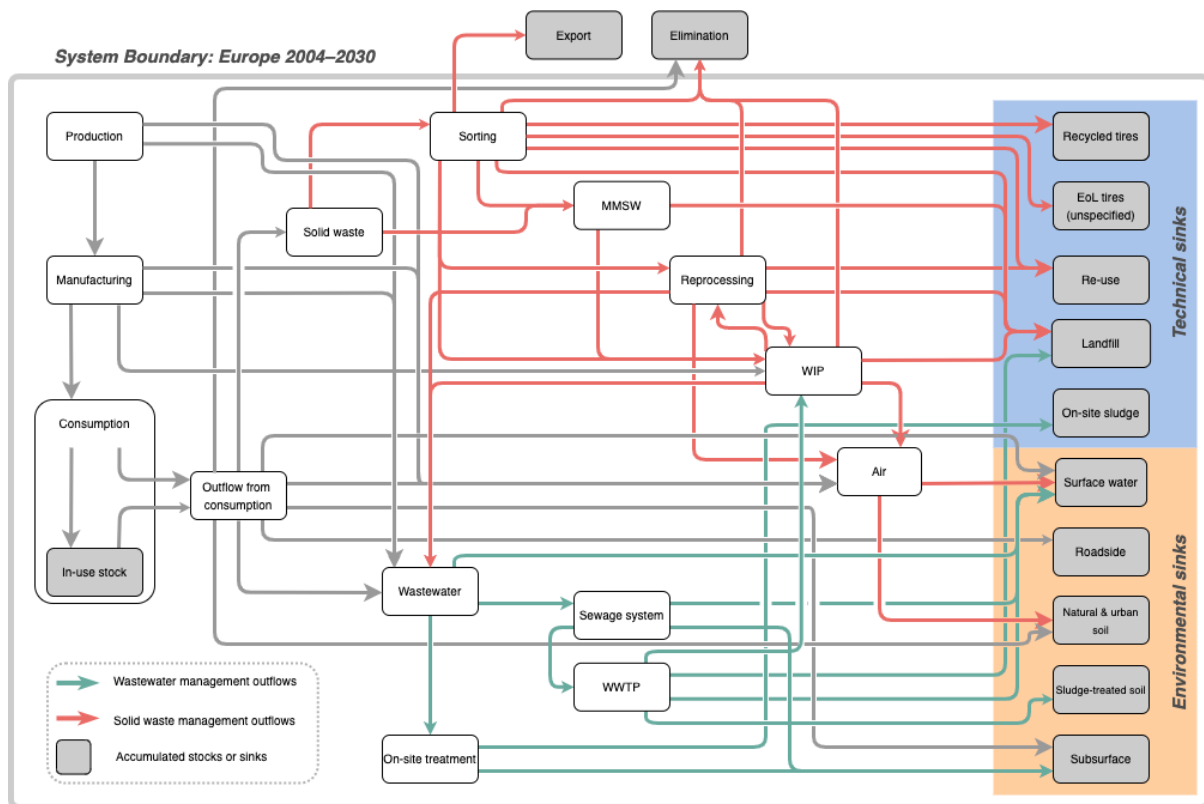


Figure S1. System boundary for the material flow analysis. Technical compartments and processes are shown in white boxes. Gray boxes represent sinks and flows leaving the system boundary. Elimination: through oxidation, graphene is transformed into carbon dioxide; Recycled tires: 'Material recycling' in the original study by Sieber et al.<sup>1</sup>; EoL tires (unspecified): 'Unknown' flow from end-of-life tires in the original study by Sieber et al. (2020)<sup>1</sup>; MMSW: Mixed municipal solid waste; WIP: Waste incineration plant; WWTP: Wastewater treatment plant.

## 1.2 Uncertainty

The present model's probabilistic nature enabled us to consider a range of input variable values (e.g., production volumes) and coefficients for defining flows (i.e., product categories, transfer coefficients) and estimating the model's outputs (e.g., inflows, outflows, sink sizes). Although uncertainty and variability both lead to estimated ranges of values, there is a clear distinction between them. Uncertainty indicates the likelihood of certain estimations, whereas variability characterizes observation-based data.<sup>1</sup> For example, this study's production volumes were characterized using probability distributions based on the minimum, maximum, and mean values from different data sources. Some years (e.g., 2026–2030) only had a single available data source. Hence, data variability governs the distribution of the initial flows into the system boundary from the production that will begin during these years. On the other hand, outputs should be addressed using uncertainty to discuss the likelihood of observing the results.

## 1.3 Distributions

### 1.3.1 Triangular distribution

A triangular distribution is used when only a single data source of minimum, mean and max values are available for the transfer coefficient (TC). TC stands for the flow fraction from one compartment to another. The mean value is used as the mode of this distribution.

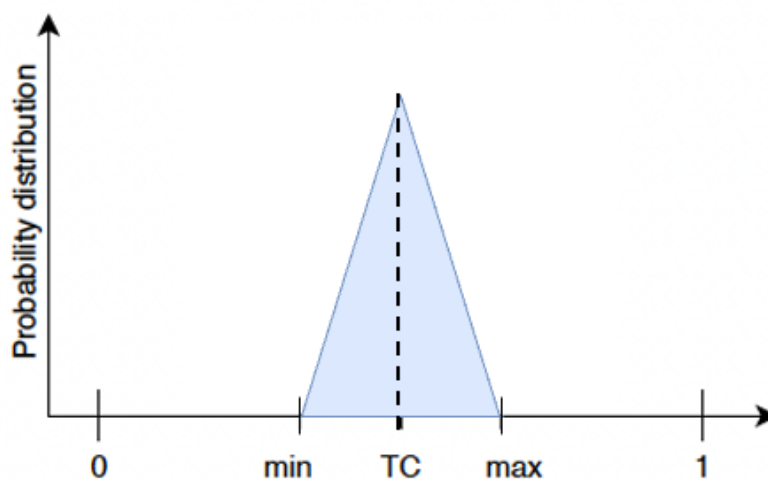


Figure S2. Schematic representation of triangular distribution.

### 1.3.2 Uniform distribution

A uniform distribution is used when there is no information available for a TC and the associated probability distribution is defined between 0 and 1.

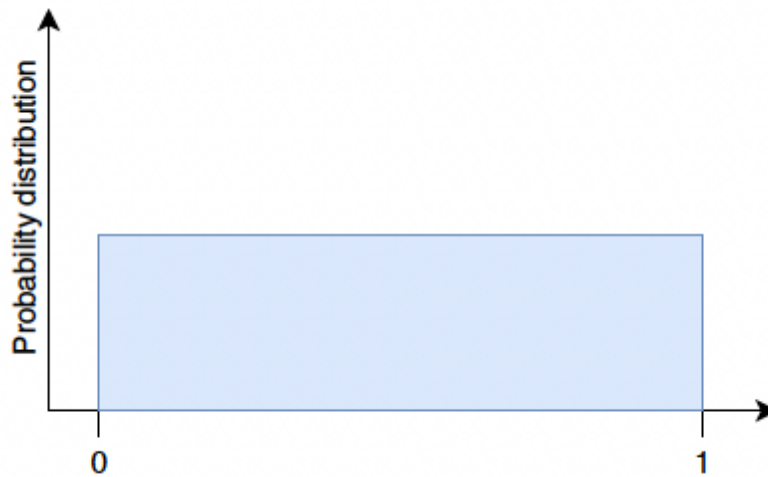


Figure S3. Schematic representation of a uniform distribution.

### 1.3.3 Trapezoidal distribution

A trapezoidal distribution is applied when two data points are available. As shown in Figure S4, it is a combination of two triangular distributions and one uniform distribution.

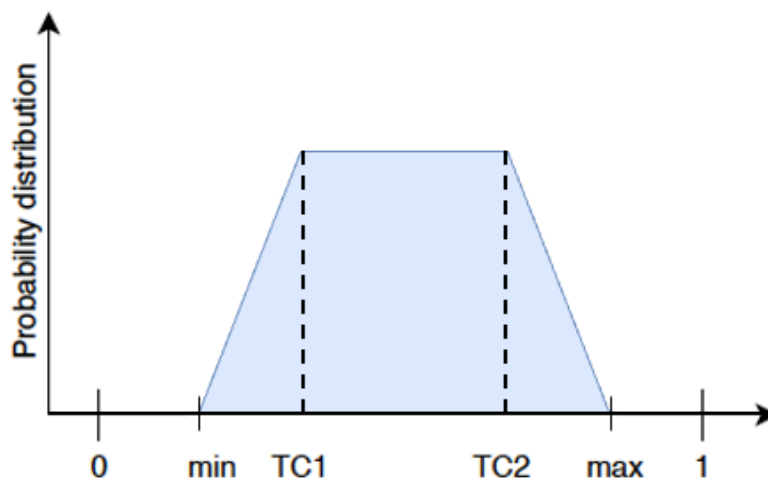


Figure S4. Schematic representation of a trapezoidal distribution.

## 2 Production volume

Table S1. Estimated graphene production volumes in Europe from 2004–2030 (in metric tonnes rounded to two significant figures).

	Estimated European graphene production volumes		
	Lower boundary	Average	Upper boundary
2004	0	0	0
2005	0.0049	0.061	0.24
2006	0.011	0.14	0.55
2007	0.019	0.24	0.91
2008	0.038	0.48	1.9
2009	0.075	0.94	3.7
2010	0.17	2.2	8.4
2011	0.39	4.9	19
2012	0.79	9.9	38
2013	1.4	18	69
2014	2.1	26	100
2015	2.9	36	140
2016	3.8	47	180
2017	4.4	55	220
2018	5.5	69	270
2019	7.2	80	300
2020	9.1	86	340
2021	14	120	450
2022	23	160	660
2023	33	220	920
2024	51	310	950
2025	79	460	2,000
2026	390	900	2,700
2027	520	1,200	3,700
2028	660	1,500	4,700
2029	820	1,900	5,800
2030	1,000	2,400	6,900

### 3 Product category allocation

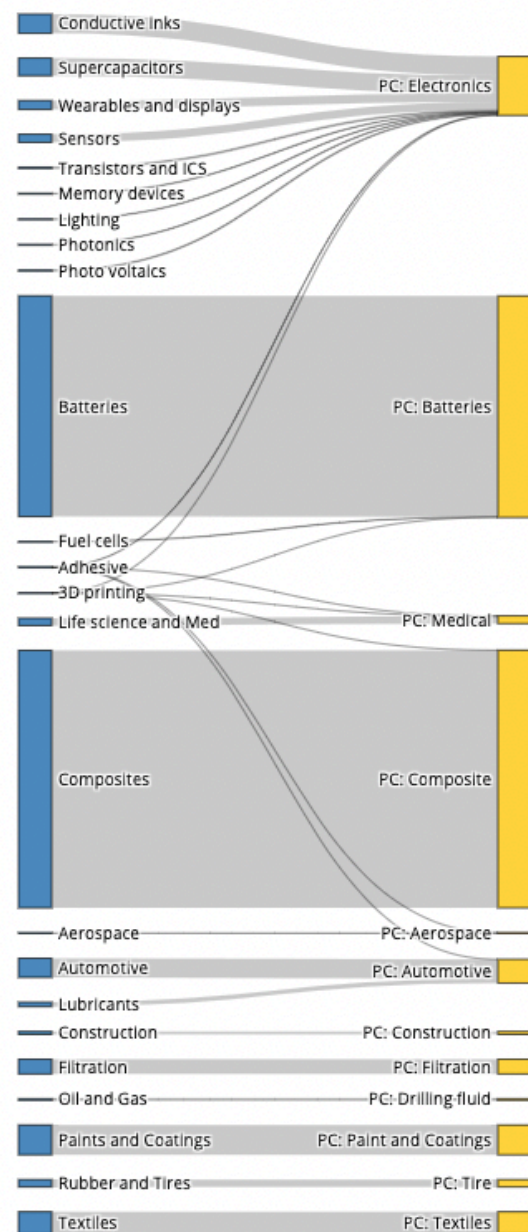


Figure S5. Product category sizes for GBMs in 2018. Blue nodes indicate product categories identified in Future Markets' report<sup>2</sup>, and yellow nodes show the product categories considered in the present study. PC: product category. Note that GBMs are expected to be used for wind turbine blades after 2022 and, therefore, this product category is not included.

Table S2. Product categories and amounts identified in Future Markets' report, and new product categories used in the rest of the present study in 2018. PC\_FutureMarket: product categories identified by Future Markets<sup>2</sup>; PC\_allocated: new product categories used in the present study.

Source		Target and link			Notes
PC_FutureMarket	Volume in tonnes	PC_allocated	% from the source	Flow volumes in metric tonnes	
3-D printing	0.5	Electronics	0.25	0.125	
		Batteries	0.25	0.125	
		Medical	0.25	0.125	
		Composites	0.25	0.125	
Adhesives	0.7	Electronics	0.5	0.35	<ul style="list-style-type: none"> <li>• structural adhesives: in the aerospace and automotive sectors; bio-adhesives (in flexible packaging and medical implants).</li> <li>• Improved thermal management in electronics:</li> </ul>
		Aerospace	0.1	0.07	
		Automotive	0.2	0.14	
		Medical	0.2	0.14	
Conductive inks	1.5	Electronics	1	13	
Wearables and displays	6	Electronics	1	6	
Transistors and ICS	0.9	Electronics	1	0.9	
Memory devices	0.5	Electronics	1	0.5	
Lighting	0.5	Electronics	1	0.5	
Photonics	0.5	Electronics	1	0.5	
Photovoltaics (solar)	0.7	Electronics	1	0.7	
Sensors	5.5	Electronics	1	5.5	
Supercapacitors	12	Electronics	1	12	
Automotive	13	Automotive	1	13	
Aerospace	0.5	Aerospace	1	0.5	
Batteries	150	Batteries	1	150	
Composites	175	Composite	1	175	
Construction	2	Construction	1	2	
Filtration	10	Filtration	1	10	
Fuel cells	0.4	Batteries	1	0.4	
Life science and medicine	5	Medical	1	5	
Lubricants	3	Automotive	1	3	<ul style="list-style-type: none"> <li>• Directly incorporated into pastes, oils, and grease, and providing significant reductions in sliding and rolling friction.</li> <li>• Graphene nanoplatelets within base oils reduce the friction and wear of metal surfaces; they can be used in both wet and dry applications.</li> </ul>
Oil and gas	1	Drilling	1	1	
Paints and coatings	20.2	Paints/coatings	1	20.2	
Rubber and tires	5	Tire	1	5	Tire additives
Textiles	15	Textiles	1	15	

## 4 Raw data on time dynamics of market entry

Table S3. Year of market entry of various product categories

<b>Product category</b>	<b>Market entry year</b>	<b>Sources</b>
Electronics	2014	3
Batteries	2014	3
Wind turbines	2023	Expert opinion
Sporting goods	2013	4,5
Water filter	2015	3
Paint and coatings	2015	3
Tire	2015	3
Textiles	2018	2



## 5 Transfer coefficients during use and EoL

### 5.1 Transfer coefficients for new product categories

Table S4. The mean value of transfer coefficients for tire applications. Values are based on the MFA results of a previous study.<sup>6</sup> EoL: end-of-life.

<b>From</b>	<b>To</b>	<b>Share (%)</b>
Rubber	EoL	78.9%
Rubber	Use	21.1%
Use	Soil	1.5%
Use	Surface Waters	15.6%
Use	Elimination	26.7%
Use	Roadside	56.3%
EoL	Elimination	58.1%
EoL	Recycled tires	1.5%
EoL	Export	37.4%
EoL	Landfill	10 <sup>-7</sup> %
EoL	EoL tires (unspecified)	3%

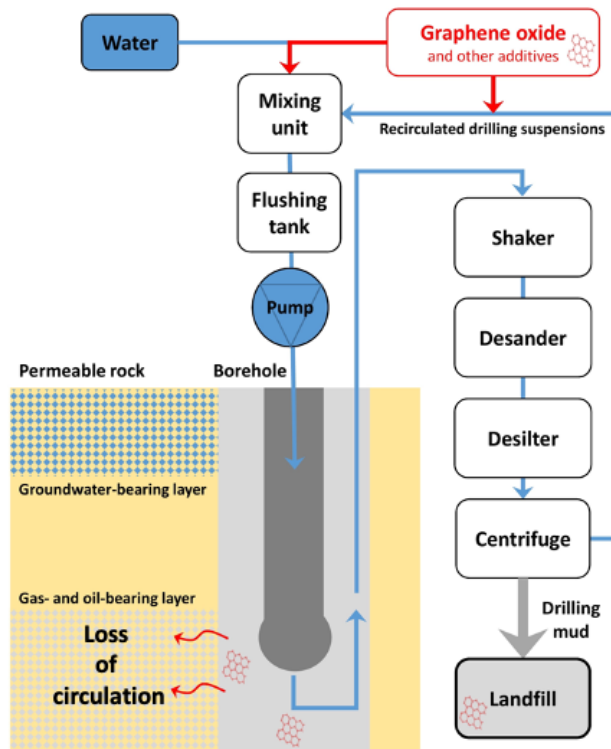


Figure S6. Simplified drilling fluid release diagram

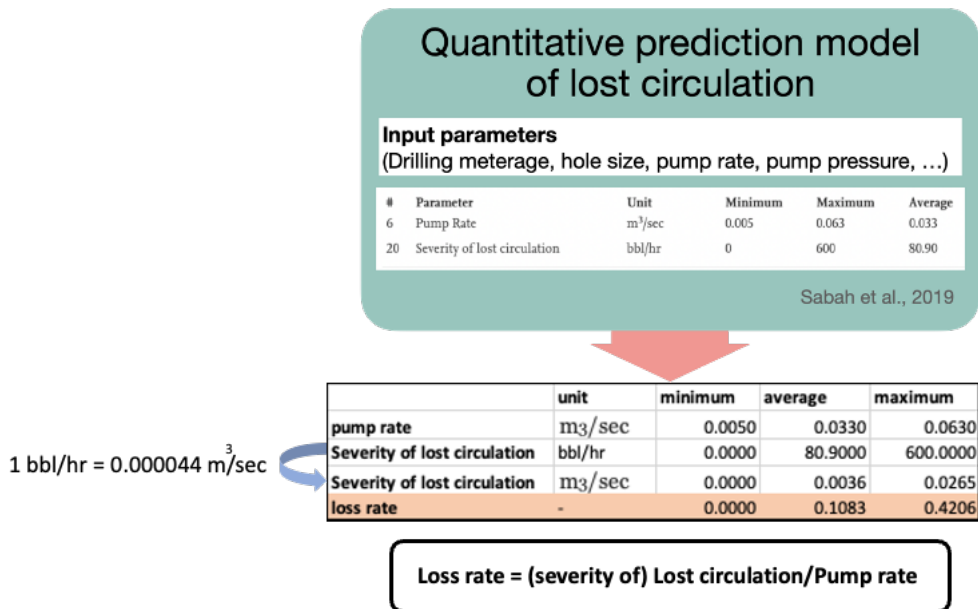


Figure S7 The illustration of the calculation of the loss rate<sup>7</sup>

## 5.2 Transfer coefficients for reprocessing

Table S5. Transfer coefficients related to reprocessing<sup>8</sup>

<b>From</b>	<b>To</b>	<b>Share (%)</b>
Textile reprocessing	Air	2.07%
Textile reprocessing	Wastewater	0.01%
Textile reprocessing	Reuse	91.06%
Textile reprocessing	Landfill	5.95%
Textile reprocessing	Waste incineration plant	0.91%
Metals reprocessing	Air	0.02%
Metals reprocessing	Elimination	0.9998%
Glass reprocessing	Air	100%
Minerals reprocessing	Air	16.31%
Minerals reprocessing	Reuse	30.74%
Minerals reprocessing	Landfill	52.95%

## References

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