

## SUPPLEMENTARY MATERIALS

# Environmental life cycle assessment of refrigerator modelled with application of various electricity mixes and technologies

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### Life-cycle stages of the analysed refrigerator—description

- **Production of raw materials and packaging (PRMP)**—this stage includes the activities of suppliers producing construction materials and refrigerator packaging (primary and secondary). The total weight of the product including packaging is 83.7 kg. The refrigerator and its packaging are composed of 17 materials (Table 1 in the main text). The production of these materials involves direct energy consumption (electricity and/or heat) in the production process itself and indirect consumption resulting from the activities of subcontractors. Let us assume that in our analysis the suppliers of the following four materials provide primary data on their activities: phenyl isocyanate (6.479 kg per refrigerator), primary aluminium (2.189 kg per refrigerator), copper (1.308 kg per refrigerator) and low-alloyed steel (32.093 kg per refrigerator). Next, let us assume that the supplier of phenyl isocyanate operates in Austria (AT), the steel and copper suppliers in Poland (PL), and the aluminium supplier runs its business in Germany (DE). For the sake of simplicity, let us assume that the remaining materials are produced in Europe (EUR) without indicating their location. The electricity consumption in the production process of the listed materials is as follows: 0.333 kWh/kg phenyl isocyanate; 0.095 kWh/kg aluminium, primary, ingot; 0.547 kWh/kg copper; 0.0219 kWh/kg converter low-alloyed steel and 0.4236 kWh/kg electric low-alloyed. In our analysis, we will model the production of these materials in two scenarios. First, we assume that the suppliers use electricity untracked with any Energy Attribute Certificates (e.g. Guarantees of Origin) [1]. Then, in the second scenario, we assume that they consume renewable tracked electricity during their production processes. In the first case, we will use national specific residual mixes modelled according to the share of energy carriers listed for 2020 by the Association of Issuing Bodies (AIB) for individual countries [2]. The residual electricity mixes for Germany and Poland differ significantly. In the German mix a much higher share of nuclear and gas electricity is visible while in the Polish case electricity from coal has a dominant share. In the second case, we will assume that the aluminium supplier has a guarantee of origin for hydro electricity, the copper supplier for photovoltaic electricity and the steel supplier for wind electricity. Austria is an exceptional case here. According to AIB's statistics, 100% of electricity was tracked in Austria in 2020 [2], which means that there is no residual mix for that country (it is zero). This also means that a supplier operating in Austria must use electricity covered by the tracking system and contractual instruments. For this reason, in our analysis, the process of generating the energy used to produce phenyl isocyanate will be modelled only as photovoltaic electricity. In any case, country-specific datasets for energy generation (AT, DE, PL) will be used. Consumption of other materials during energy generation will be modelled using averaged energy mixes representative of Europe.



- **Transport of materials and packaging to manufacturer (TRAN)**—the second stage involves transporting raw materials and packaging from suppliers to the refrigerator production site. The following transport distances have been assumed: 250 km for the supply of aluminium and copper, 570 km for the supply of steel, 670 km for the supply of phenyl isocyanate and 1000 km for the other materials. It is assumed that a truck with a 16–32t maximum total weight authorised and a EURO4 emission standard is used for transport. Table 1 summarises the transport data.
- **Manufacturing of refrigerator (MAN)**—we assume that the refrigerator production process takes place in Poland and that all the suppliers of auxiliary materials (compressed air, heat, steam) also operate in Poland. The direct electricity consumption for the production of one refrigerator is 10.948 kWh. The remaining (intermediate) consumption results from the manufacture of auxiliary materials by suppliers. In the first analysis variant, all electrical power consumption (direct and consumption by suppliers) will be modelled as the residual mix for Poland. In the second variant, we assume that the direct energy consumption by the refrigerator manufacturer is covered by renewable energy from photovoltaics (which means that either the refrigerator manufacturer has its photovoltaic installation on-site or it buys electricity with a guarantee of origin from a supplier).
- **Distribution of refrigerators (DISTR)**—the distribution stage includes both transport and storage. In our example, we have assumed that the storage period for the refrigerator at the distribution centres is 10 days and that a refrigerator on a pallet takes up an area of 0.96 m<sup>2</sup>. Based on this, we estimated the energy and heat consumption of the distribution centre. This amounts to 0.789 kWh of electricity and 9.468 MJ of heat from natural gas. We assumed that storage only takes place in Poland and the energy consumption was modelled using the electricity supplier mix for Poland for the year 2020. Transport of the finished product has been broken down according to the destination country of the refrigerator. Our analysis has been performed per one refrigerator, but it should reflect the sales structure of the full production volume of these refrigerators in the reference period (annual production volume in 2020). Three variants have been assumed: 100% of the refrigerators are marketed in Poland (100% PL), half of the refrigerators are marketed in Poland, and half in Germany (50% PL, 50% DE), and all the refrigerators produced are exported to Germany (100% DE). Depending on the target country, different transport distances were assumed (500 km distribution to the Polish market, 1000 km distribution to the German market). Therefore, there is no differentiation in the energy mix for the distribution stage, as only the electricity supplier mix for Poland was used. However, transport indicators vary as a result of the different distances to the target countries where the refrigerators are sold.
- **Retail of refrigerator (RETA)**—retail sales are performed in the country of destination of the analysed product. In this case, we only took into account the electricity consumption of the retail outlets. We assumed that the refrigerator spends 81 days in a store (value of Days Inventory Outstanding (DIO) index for retailing of electric home appliance in Poland in 2020 [3]) and assumed that this is identical for Poland and Germany. Electricity consumption in the stores was estimated at 31.956 kWh. Depending on the scenario, this was modelled as the electricity supplier mix for Poland or Germany.
- **Use of refrigerator (USE)**—the correct use of a refrigerator, consistent with its design and operating manual, requires connection to a power outlet. In our case, we assumed that the refrigerator is of energy efficiency class F, consumes 303 kWh of electricity per year and has a lifespan of 10 years. In addition, we took into account the use of water and detergent for refrigerator cleaning (washing once a year with 10 l of water + 0.002 kg of soap) and the loss and refilling of refrigerant. At the operator stage, electricity is therefore consumed directly (3030 kWh over 10 years) and indirectly, resulting from the production of water, refrigerant, soap and wastewater treatment. Indirect consumption was modelled using the European average data, while direct consumption was modelled using the electricity supplier mix 2020 (for Poland or Germany respectively, depending on the scenario).
- **Transport of refrigerator waste and its packaging (TR)**—this step involves transporting the refrigerator at its end of life together with its packaging to the final disposal site. A distance of 100 km was assumed and it was also assumed that a truck with a 16–32t maximum total weight

authorised and a EURO4 emission standard is used for transport. Table 1 summarises the transport data.

- **End of life (EOL)**—the last stage of the life cycle covers the management of waste generated after the refrigerator is withdrawn from operation. We adopted relevant scenarios for the management of particular types of waste materials (steel, aluminium, polystyrene, polyethylene, etc.) representative of Poland or Germany (depending on the scenario), using ready-made secondary datasets from the ecoinvent 3.6 database. Energy consumption at the waste processing stage was modelled in line with the original datasets, without any modifications.

**Table S1. Scenarios used in the calculations for particular life cycle stages of refrigerator**

Production of raw materials and packaging	PRMP	Residual	<ul style="list-style-type: none"> <li>▪ Electricity directly used during the production of phenyl isocyanate modelled as Photovoltaic electricity (AT, multi Si, 570 kWp, open ground installation);</li> <li>▪ Electricity directly used during the production of primary aluminium (liquid and ingot) according to residual mix for Germany, 2020;</li> <li>▪ Electricity directly used during the production of low-alloyed steel and copper modelled according to residual mix for Poland, 2020;</li> <li>▪ Electricity directly used during the production of remaining materials modelled as the average mix for Europe.</li> </ul>
		Renewable	<ul style="list-style-type: none"> <li>▪ Electricity directly used during the production of phenyl isocyanate modelled as Photovoltaic electricity (AT, multi Si, 570 kWp, open ground installation);</li> <li>▪ Electricity directly used during the production of primary aluminium (liquid and ingot) modelled as hydro electricity (DE, pumped storage 24%; run-of-river 12%; reservoir non-alpine region 64%);</li> <li>▪ Electricity directly used during the production of copper modelled as photovoltaic electricity (PL, 3kWp, slanted-roof installation, multi Si);</li> <li>▪ Electricity directly used during production of low-alloyed steel modelled as wind electricity (PL, 1-3 MW turbine, onshore);</li> <li>▪ Electricity directly used during the production of remaining materials modelled as the average mix for Europe.</li> </ul>

Transport of raw materials	TRANS	Residual Renewable	<ul style="list-style-type: none"> <li>The same distances and the same mean of transport for both scenarios assumed: PL→PL = 250 km; DE→PL = 570km and EUR→PL = 1000km (freight lorry, 16-32t, EURO4).</li> </ul>
Manufacturing of refrigerator	MAN	Residual	<ul style="list-style-type: none"> <li>Electricity directly used during production of refrigerator modelled according to residual mix for Poland, 2020;</li> <li>Electricity directly used during the production of auxiliary materials modelled as the residual mix for Poland, 2020.</li> </ul>
		Renewable	<ul style="list-style-type: none"> <li>Electricity directly used during the production of refrigerator modelled as photovoltaic electricity (PL, 3kWp, slanted-roof installation, multi Si);</li> <li>Electricity directly used during the production of auxiliary materials modelled as photovoltaic electricity (PL, 3kWp, slanted-roof installation, multi Si).</li> </ul>
Distribution of refrigerator	DISTR	100% PL	<ul style="list-style-type: none"> <li>Electricity directly used during storage in distribution centres modelled according to supplier mix for Poland, 2020;</li> <li>Target market = 100% Poland (500 km distance).</li> </ul>
		50%PL 50%DE	<ul style="list-style-type: none"> <li>Electricity directly used during storage in distribution centres modelled according to supplier mix for Poland, 2020;</li> <li>Target market = 50% Poland (500 km distance) and 50% Germany (1000 km).</li> </ul>
		100% DE	<ul style="list-style-type: none"> <li>Electricity directly used during storage in distribution centres modelled according to supplier mix for Poland, 2020;</li> <li>Target market = 100% Germany (1000 km distance).</li> </ul>

Retail of refrigerator	RETA	100% PL	<ul style="list-style-type: none"> <li>Electricity directly used during retailing modelled according to supplier mix for Poland, 2020.</li> </ul>
		50%PL 50%DE	<ul style="list-style-type: none"> <li>Electricity directly used during retailing modelled according to supplier mix 2020, 50% for Poland and 50% for Germany.</li> </ul>
		100% DE	<ul style="list-style-type: none"> <li>Electricity directly used during retailing modelled according to supplier mix for Germany, 2020.</li> </ul>
Use of refrigerator	USE	100% PL	<ul style="list-style-type: none"> <li>Electricity directly used during use stage modelled according to supplier mix for Poland, 2020;</li> <li>Electricity directly used during the production of remaining exploitation materials modelled as the average mix for Europe.</li> </ul>
		50%PL 50%DE	<ul style="list-style-type: none"> <li>Electricity directly used during use stage modelled according to supplier mix 2020, 50% for Poland and 50% for Germany.</li> <li>Electricity directly used during the production of remaining exploitation materials modelled as the average mix for Europe</li> </ul>
		100% DE	<ul style="list-style-type: none"> <li>Electricity directly used during use stage modelled according to supplier mix for Germany, 2020;</li> <li>Electricity directly used during the production of remaining exploitation materials modelled as the average mix for Europe.</li> </ul>
Transport of waste to EoL	TRANSW	100% PL 50%PL 50%DE 100% DE	<ul style="list-style-type: none"> <li>The same distance (100 km) and the mean of transport (freight lorry, 16-32t, EURO4) assumed for all scenarios.</li> </ul>
End of life	EOL	100% PL	<ul style="list-style-type: none"> <li>The type and amount of waste assumed the same as in included in an original dataset for a refrigerator production (taken from ecoinvent database 3.6). The treatment of the waste assumed according to the country-specific waste market situation (Poland).</li> </ul>
		50%PL 50%DE	<ul style="list-style-type: none"> <li>The type and amount of waste assumed the same as in included in an original dataset for a refrigerator production (taken from ecoinvent database 3.6). The treatment of the waste assumed according to the country-specific waste market situation (50% Poland, 50% Germany).</li> </ul>
		100% DE	<ul style="list-style-type: none"> <li>The type and amount of waste assumed the same as in included in an original dataset for a refrigerator production (taken from ecoinvent database 3.6). The treatment of the waste assumed according to the country-specific waste market situation (Germany).</li> </ul>

**Table S2. The impact assessment results (single score) for a single life cycle stage – Production of Raw Materials and Packaging (PRMP)**

INPUT/OUTPUT	SCENARIO			
	PRMP_residual		PRMP_renewable	
	Pt	%	Pt	%
Steel, low-alloyed	2.96E+00	33.11%	2.72E+00	32.68%
Phenyl isocyanate	1.73E+00	19.33%	1.73E+00	20.78%
Polystyrene, high impact	1.12E+00	12.49%	1.12E+00	13.42%
Aluminium, primary, ingot	1.03E+00	11.56%	6.64E-01	7.97%
Copper	7.84E-01	8.76%	7.74E-01	9.29%
Polyol	6.70E-01	7.48%	6.70E-01	8.04%
EUR-flat pallet	4.99E-01	5.58%	4.99E-01	5.99%
HFC-152a	5.52E-02	0.62%	5.52E-02	0.66%
Polyvinylchloride	3.24E-02	0.36%	3.24E-02	0.39%
Epoxy resin, liquid	2.05E-02	0.23%	2.05E-02	0.25%
Methylcyclopentane	1.94E-02	0.22%	1.94E-02	0.23%
Polyethylene, linear low density	1.90E-02	0.21%	1.90E-02	0.23%
Plastic extrusion	4.59E-03	0.05%	4.59E-03	0.06%
Dimethyldichlorosilane	8.38E-04	0.01%	8.38E-04	0.01%
Sodium percarbonate	2.18E-04	0.002%	2.18E-04	0.003%
Sodium silicate	1.26E-04	0.001%	1.26E-04	0.002%
Aluminium fluoride	1.54E-04	0.002%	1.54E-04	0.002%
Sodium hydroxide	4.33E-05	0.0005%	4.33E-05	0.0005%
<b>Total score per the LC stage</b>	<b>8.95E+00</b>	<b>100.00%</b>	<b>8.33E+00</b>	<b>100.00%</b>

**Table S3: The impact assessment results (single score) for a single life cycle stage – Transport of raw materials and packaging (TRANS)**

INPUT/OUTPUT	SCENARIO	
	TRANS_residual and TRANS_renewable (the same for both scenarios)	
	Pt	%
Transport of low-alloyed steel and cooper (PL→PL)	4.69E-02	15.02%
Transport of aluminium ingot (DE→PL)	7.01E-03	2.24%
Transport of phenyl isocyanate (AT→PL)	2.44E-02	7.81%
Transport of remaining materials (EUR→PL)	2.34E-01	74.93%
<b>Total score per the LC stage</b>	<b>3.12E-01</b>	<b>100.00%</b>

**Table S4: The impact assessment results (single score) for a single life cycle stage— Manufacturing (MAN)**

INPUT/OUTPUT	SCENARIO			
	MAN_residual		MAN_renewable	
	Pt	%	Pt	%
Water from nature and HFC-152 emission	6.92E-01	38.68%	6.92E-01	56.23%
Compressed air	4.81E-01	26.89%	2.83E-01	22.98%
Electricity	4.11E-01	23.00%	5.13E-02	4.17%
Metal working factory	1.63E-01	9.14%	1.63E-01	13.29%
Heat	4.08E-02	2.28%	4.08E-02	3.32%
Wastewater treatment	1.09E-04	0.01%	1.09E-04	0.01%
Energy and auxilliary inputs, metal working factory	2.31E-10	0.00%	1.84E-10	0.00%
<b>Total score per the LC stage</b>	<b>1.79E+00</b>	<b>100.00%</b>	<b>1.23E+00</b>	<b>100.00%</b>

**Table S5: The impact assessment results (single score) for a single life cycle stage— Distribution (DISTR)**

INPUT/OUTPUT	SCENARIO					
	DISTR_100%PL		DISTR_50%PL50%DE		DISTR_100%DE	
	Pt	%	Pt	%	Pt	%
Transport	2.40E-01	84.47%	3.59E-01	89.08%	4.79E-01	91.58%
Storage - electricity	2.84E-02	10.01%	2.84E-02	7.04%	2.84E-02	5.43%
Storage - heat	1.57E-02	5.52%	1.57E-02	3.88%	1.57E-02	2.99%
<b>Total score per the LC stage</b>	<b>2.84E-01</b>	<b>100.00%</b>	<b>4.04E-01</b>	<b>100.00%</b>	<b>5.23E-01</b>	<b>100.00%</b>

**Table S6: The impact assessment results (single score) for a single life cycle stage— Retail (RETA)**

INPUT/OUTPUT	SCENARIO					
	RETA_100%PL		RETA_50%PL50%DE		RETA_100%DE	
	Pt	%	Pt	%	Pt	%
Electricity	1.20E+00	100.00%	7.11E-01	100.00%	2.71E-01	100.00%
<b>Total score per the LC stage</b>	<b>1.20E+00</b>	<b>100.00%</b>	<b>7.11E-01</b>	<b>100.00%</b>	<b>2.71E-01</b>	<b>100.00%</b>

**Table S7: The impact assessment results (single score) for a single life cycle stage— Use (USE)**

INPUT/OUTPUT	SCENARIO					
	USE_100%PL		USE_50%PL50%DE		USE_100%DE	
	Pt	%	Pt	%	Pt	%
Electricity	1.13E+02	99.91%	6.74E+01	99.85%	2.57E+01	99.62%
HFC-152 emission	6.86E-02	0.06%	6.86E-02	0.10%	6.86E-02	0.27%
Soap	1.82E-02	0.02%	1.82E-02	0.03%	1.82E-02	0.07%
Tap water	5.97E-03	0.01%	5.97E-03	0.01%	5.97E-03	0.02%
HFC-152 production	5.50E-03	0.00%	5.50E-03	0.01%	5.50E-03	0.02%
Wastewater treatment	-2.64E-04	0.00%	-2.64E-04	0.00%	-2.64E-04	0.00%
<b>Total score per the LC stage</b>	<b>1.13E+02</b>	<b>100.00%</b>	<b>6.75E+01</b>	<b>100.00%</b>	<b>2.58E+01</b>	<b>100.00%</b>

**Table S8: The impact assessment results (single score) for a single life cycle stage— Transport of waste (TRANSW)**

INPUT/OUTPUT	SCENARIO					
	TRANSW_100%PL		TRANSW_50%PL50%DE		TRANSW_100%DE	
	Pt	%	Pt	%	Pt	%
Transport	4.79E-02	100.00%	4.79E-02	100.00%	4.79E-02	100.00%
<b>Total score per the LC stage</b>	<b>4.79E-02</b>	<b>100.00%</b>	<b>4.79E-02</b>	<b>100.00%</b>	<b>4.79E-02</b>	<b>100.00%</b>

**Table S9: The impact assessment results (single score) for a single life cycle stage— End of Life (EOL)**

INPUT/OUTPUT	SCENARIO					
	EOL_100%PL		EOL_50%PL50%DE		EOL_100%DE	
	Pt	%	Pt	%	Pt	%
Treatment of waste polystyrene, municipal incineration	1.47E-01	40.88%	3.59E-01	70.22%	5.70E-01	86.17%
Treatment of waste polyvinylchloride, open burning (PL)/municipal incineration (DE)	6.58E-02	18.27%	3.30E-02	6.45%	1.67E-02	2.53%
Treatment of waste polystyrene, open burning	3.14E-02	8.73%	1.57E-02	3.08%	-	-
Remaining processes	1.16E-01	32.12%	1.03E-01	20.25%	7.48E-02	11.30%
<b>Total score per the LC stage</b>	<b>3.60E-01</b>	<b>100.00%</b>	<b>5.11E-01</b>	<b>100.00%</b>	<b>6.62E-01</b>	<b>100.00%</b>

**Supplementary Information – references:**

1. DIRECTIVE (EU) 2018/2001 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 11 December 2018 on the promotion of the use of energy from renewable sources <https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32018L2001&from=EN> (accessed on 15 June 2021).
2. Association of Issuing Bodies. European Residual Mixes Results of the calculation of Residual Mixes for the calendar year 2020 AIB report Version 1.0, 2021-05-31 <https://www.aib-net.org/facts/european-residual-mix> (accessed on 7 June 2021).
3. Industry Monitoring. Sectoral analyses (original title: Monitoring Branżowy Analizy Sektorowe). PKO BP, 2021 [https://www.pkobp.pl/media\\_files/60520c91-1281-4e6e-94d4-d041d91f679e.pdf](https://www.pkobp.pl/media_files/60520c91-1281-4e6e-94d4-d041d91f679e.pdf) (accessed on 7 June 2021).