# Supplementary Information of "Upcycling industrial heritage into fossil-free Infrastructure: Role of iron fuel for the European energy system"

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# SI1 - Scenario of Thiran: a fossil-free energy system for Europe by 2050

This section gives a more complete description of the fossil-free European energy system from which the analysis is based. Interested readers could find more details about the methodology used to obtain such prediction in [1], while main results interesting for the scope of this work are detailed below.

Results from this fossil- and nuclear-free European energy system show that renewables are key and become the dominant source of energy. Wind and solar account for the majority of energy generation (69%), with output in 2050 reaching 8.5 times and 21 times current levels, respectively. Hydropower contributes only to 4% of total energy but plays a key role in system flexibility.

From the gross available energy, several energy carriers are used to meet hourly end-use demand in each country. Electricity is the dominant energy carrier (52%), reflecting a highly electrified system. In addition to dedicated electricity uses, electricity is used in other applications, including high-temperature industrial heat, heat pumps for low-temperature heat, electric vehicles, space cooling, etc. Moreover, a substantial share of electricity (∼65%) is also used to produce electrofuels.

Those electrofuels plus biofuels represent the second-largest category of final energy carriers (43%), called renewable fuels. They are used across a wide range of applications, highlighting the continued role of fuels where direct electrification is not feasible. Biomass and hydrogen are the primary resources, used either directly or upgraded into secondary fuels such as ammonia, methane, and methanol.

Biomass is sourced from three feedstocks with distinct costs, availability, and uses: woody biomass (69%), biowaste (18%), and wet biomass (13%). Woody biomass and biowaste are directly combusted in industrial furnaces to provide high-temperature heat, from which only the substitution of woody biomass with iron is considered in this work.

Hydrogen is produced from renewable electricity via electrolysis. Of this, 58% is used directly in fuel-cell trucks for freight transport, while the remainder is converted into secondary fuels for specific applications, storage, and energy exchange, notably through ammonia synthesis (Haber–Bosch) and methanation. Methane is the second most produced advanced fuel, primarily used for bus transport (50%). It also contributes to power generation and system flexibility, with 33% consumed in CCGT. Although produced in smaller quantities, methanol and ammonia play key roles in specific sectors. Methanol is mainly used as a feedstock for non-energy demand and as the primary fuel for inland freight shipping. Ammonia, in turn, is the main fuel for maritime cargo transport and is also used for fertilizer production and in small-scale CCGT to provide

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flexibility. Accordingly, iron powder is considered in this work as a potential substitute to the use of methane and ammonia in CCGT.

Using iron powder to store and transport green hydrogen would enlarge the variety of renewable fuels. It could thus play a key role in future energy mix as they provide flexibility by being produced during periods of high renewable electricity generation and stored for later use. They are primarily used for seasonal storage, typically in the form of liquid, gaseous, or even solid (for iron) fuels rather than hydrogen itself. Beyond storage, renewable fuels also play a key role in cross-border energy exchanges. Hydrogen is the main traded resource, accounting for 35% of exchanges, and is transported via a dedicated network combining retrofitted methane pipelines and new infrastructure, justifying the assumption taken in this work to find the hydrogen fluxes illustrated in Figure SI1. In contrast, liquid and solid fuels are transported by freight. While this scenario does not consider dedicated transport networks for these carriers, transport infrastructure is analyzed in this study for the use of iron.

The main energy importers are Germany (496 TWh), the Netherlands (337 TWh), and Belgium (154 TWh), which is consistent with the exports of iron towards Germany estimated in this study. These countries combine high population density, energy-intensive industries, and major trade hubs, resulting in strong demand for shipping and freight. Their relatively limited renewable potential further increases reliance on imports. These countries combine high population density, energy-intensive industries, and major trade hubs, resulting in strong demand for shipping and freight. Their relatively limited renewable potential further increases reliance on imports.

Europe's optimal design for a fossil-free energy system does not rely on imports from outside the system. This reflects the existence of substantial untapped renewable resources, which can be used directly or converted into fuels at competitive costs. These domestic resources are key to enhancing Europe's energy security and independence.

# SI2 - List of considered European countries and country codes

This study considers the same 34 European countries as in the work of Thiran described in the previous section, including the 25 continental EU Member States (the 27 without Cyprus and Malta), the United Kingdom, Norway, Switzerland, and six non-EU Balkan countries (Albania, Bosnia-Herzegovina, Kosovo, Montenegro, North Macedonia, and Serbia). The complete list is presented in Table SI1.

Table SI1: List of considered European countries and country codes

| Country | Code |
|---|---|
| Albania | ALB |
| Austria | AUT |
| Belgium | BEL |
| Bosnia and Herzegovina | BIH |
| Bulgaria | BGR |
| Croatia | HRV |
| Czech Republic | CZE |
| Denmark | DNK |
| Finland | FIN |
| France | FRA |
| Germany | DEU |
| Greece | GRC |
| Hungary | HUN |
| Ireland | IRL |
| Italy | ITA |
| Kosovo | KOS |
| Latvia | LVA |
| Montenegro | MNE |
| Netherlands | NLD |
| North Macedonia | MKD |
| Poland | POL |
| Portugal | PRT |
| Romania | ROU |
| Serbia | SRB |
| Slovakia | SVK |
| Slovenia | SVN |
| Spain | ESP |
| Sweden | SWE |
| Estonia | EST |
| Switzerland | CHE |
| Lithuania | LTU |
| Luxembourg | LUX |
| Norway | NOR |
| United Kingdom | GBR |

# SI3 - Iron mass required per time period for each country with a heat demand higher than 100 GWh accounting for the cement factories infrastructure

The comparison between the share of high-temperature heat demand associated with cement production and the existing infrastructure leads to the demand for iron powder detailed in Table SI2. The heat demand reaches between 0.1 to 0.9 $\mathrm{Mt_{Fe}}$ per country and period, with associated annual CF of 38.5-98.6%. During autumn–winter, most plants operate continuously (periodic CF of 60.9–100%), while only those from specific countries remain active in spring (periodic CF of 42.7–100%). In summer–autumn, spring-active plants continue with slightly higher periodic CF (65.6–100%), while others run at 20–69.5%.

Table SI2: Iron mass in [Mt] required to supply cement high-temperature heat demand in each country accounting for the existing, announced, and mothballed infrastructure, and the associated periodic capacity factor of the plants (in parenthesis).

| [$\mathrm{Mt_{Fe}}$] | Autumn-winter | Spring | Summer-autumn | Total |
|---|---|---|---|---|
| AUT | 0.9 (87.4-93%) | | 0.5 (44.2-48.1%) | 1.4 |
| BIH | 0.1 (99.3%) | 0.1 (97.8%) | 0.1 (98.9%) | 0.3 |
| BEL | 0.9 (82.4-89.8%) | | 0.3 (20.5-33.9%) | 1.2 |
| CZE | 0.3 (86.9%) | | 0.2 (43.6%) | 0.5 |
| DEU | 0.7 (87.2-87.6%) | | 0.2 (20-26.8%) | 0.9 |
| ESP | 0.5 (87.3%) | | 0.2 (41.1%) | 0.7 |
| EST | 0.1 (87.2%) | | 0.2 (23.9%) | 0.3 |
| FIN | 0.6 (100%) | 0.4 (100%) | 0.6 (100%) | 1.6 |
| HRV | 0.1 (98.2%) | 0.1 (76.7%) | 0.1 (89.5%) | 0.3 |
| IRL | 0.2 (85.4%) | 0.1 (69.2%) | 0.1 (66%) | 0.4 |
| LVA | 0.1 (99.2%) | 0.1 (97.5%) | 0.1 (98.8%) | 0.3 |
| NLD | 0.5 (76.1-87.8%) | | 0.2 (26-35.6%) | 0.7 |
| NOR | 0.1 (60.9%) | 0.1 (98.7%) | 0.2 (85%) | 0.4 |
| POL | 0.3 (71.6%) | 0.1 (42.7%) | 0.3 (65.6%) | 0.7 |
| ROM | 0.8 (99.7-100%) | 0.5 (90.3-100%) | 0.8 (97.3-100%) | 2.1 |
| SWE | 0.4 (64.8-71.1%) | 0.4 (98.9%) | 0.6 (83.3-84.3%) | 1.4 |
| SVN | 0.1 (92.8%) | | 0.1 (58.2%) | 0.2 |
| SVK | 0.2 (87.6-88.3%) | | 0.1 (69-69.5%) | 0.3 |
| Total | 6.9 | 1.9 | 4.9 | 13.7 |

# SI4 - Hydrogen mass fluxes from countries with a higher hydrogen production than their DRI capacity to countries needing hydrogen to fully use their DRI capacity

The assumption taken in this work that the total DRI capacity is used implies that countries with insufficient hydrogen production compared to their DRI capacity must import hydrogen. Accordingly, hydrogen is exported to countries where production is insufficient (Belgium, Germany, Netherlands, Sweden, Finland) using the existing natural gas pipeline network [2]. The resulting hydrogen fluxes reach 0.01 to 0.15 $\mathrm{Mt}_{\mathrm{H2}}$ (see Figure SI1), consistent with 2050 hydrogen transport network projections [3].

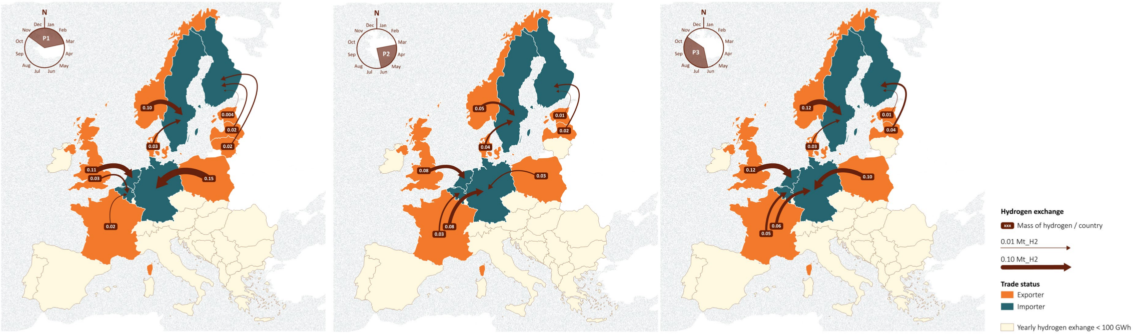


Figure SI1: Hydrogen mass fluxes for each period to maximize the DRI reduction capacity used.

# SI5 - Representation of the means of transport for spring and summer-autumn

After estimating the transport fleet between plants based on the computed global iron fluxes between countries, the daily fleet can be represented for each period and scenario. While the results for the autumn-winter period are illustrated in the original paper, the representation of the fluxes for spring and summer-autumn is presented in Figure SI2 and Figure SI3, respectively. Nevertheless, these results have already been included in the estimation of the daily fleet discussed in the manuscript.

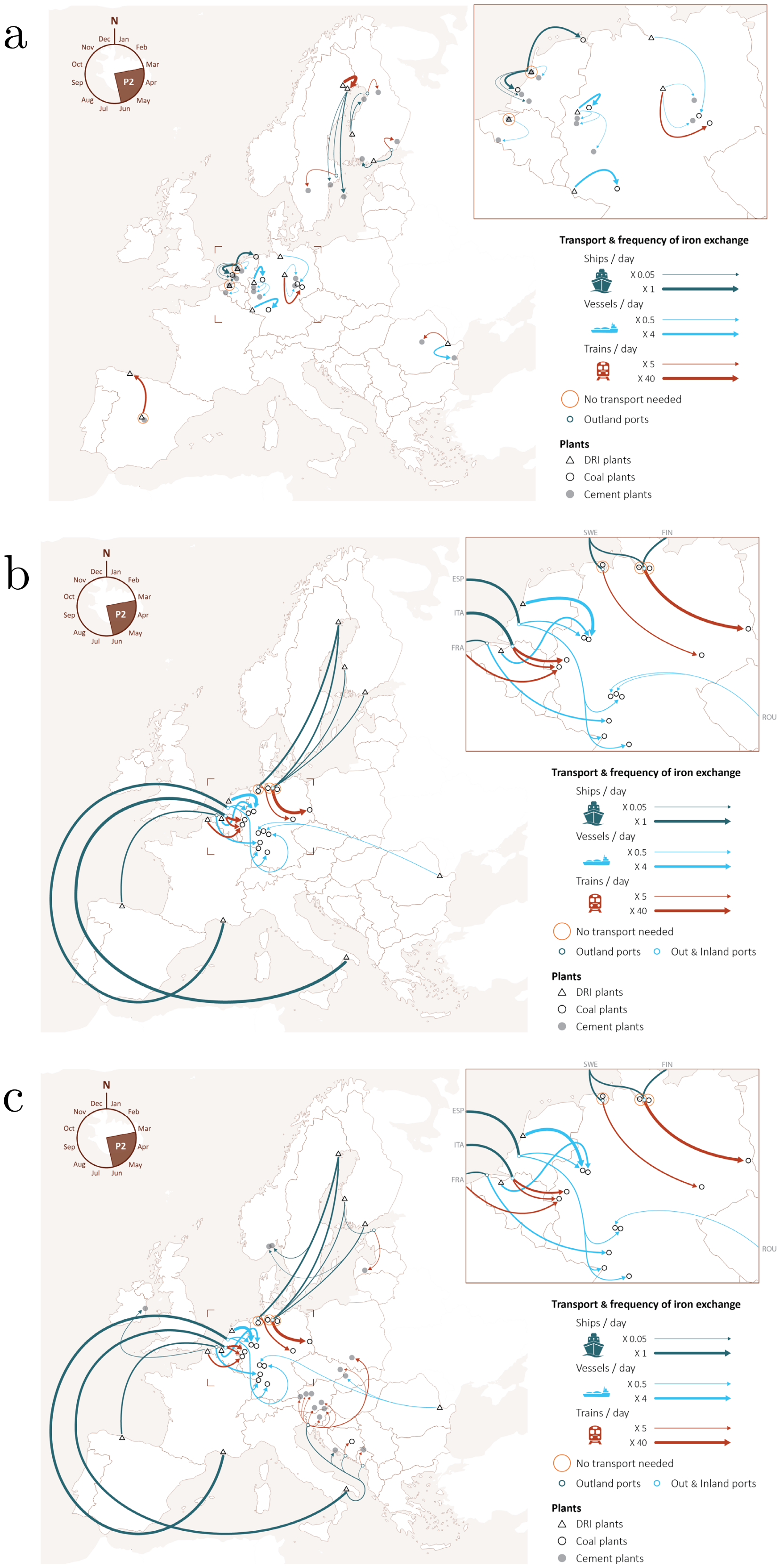


Figure SI2: Means of transport required during spring for the iron fluxes associated with (a) the direct use of iron in the countries where it is reduced, (b) the electricity-driven scenario, and (c) the heat-driven scenario. In each case, a zoom on Belgium, Netherlands, and Germany is displayed.

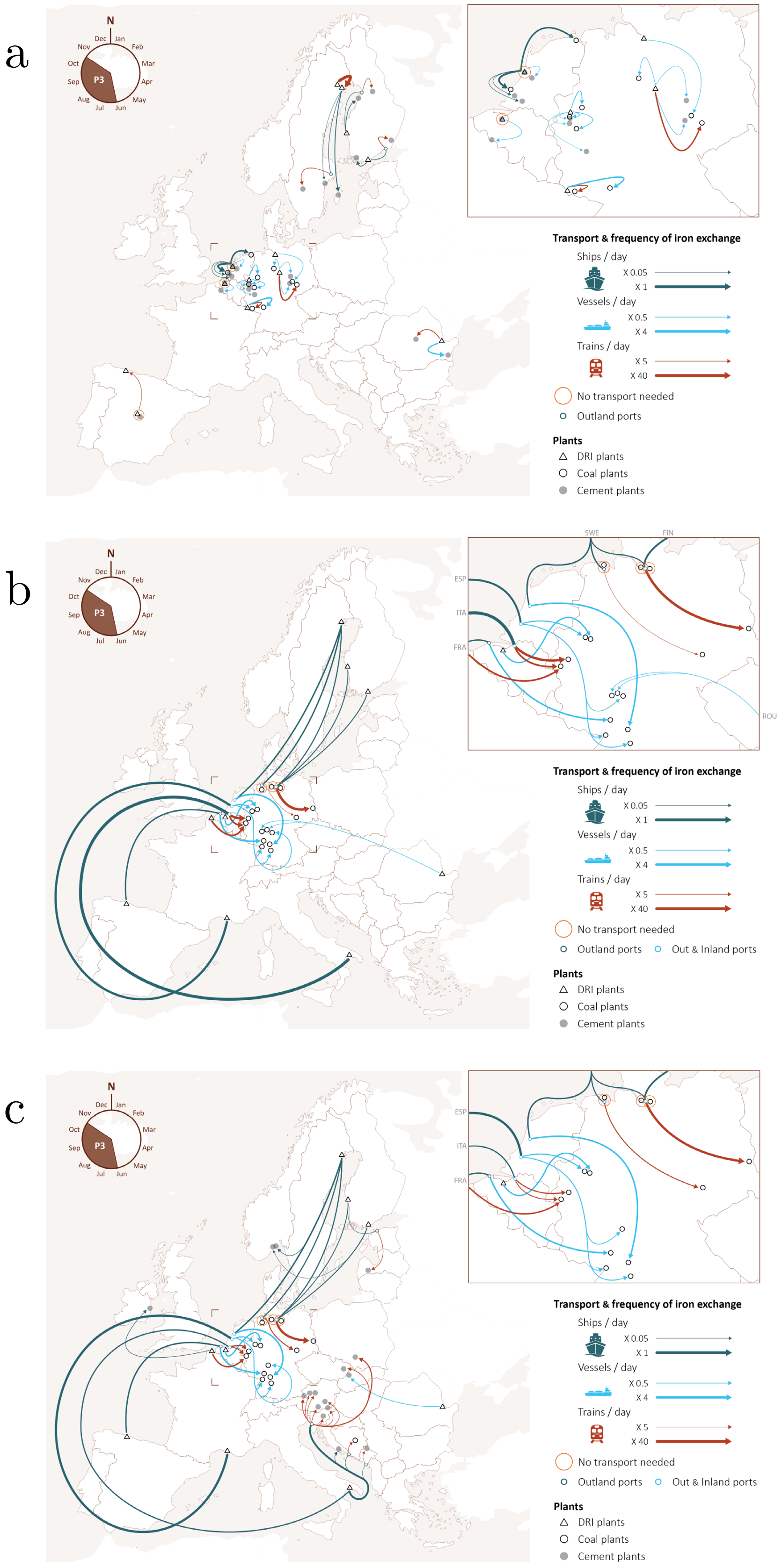
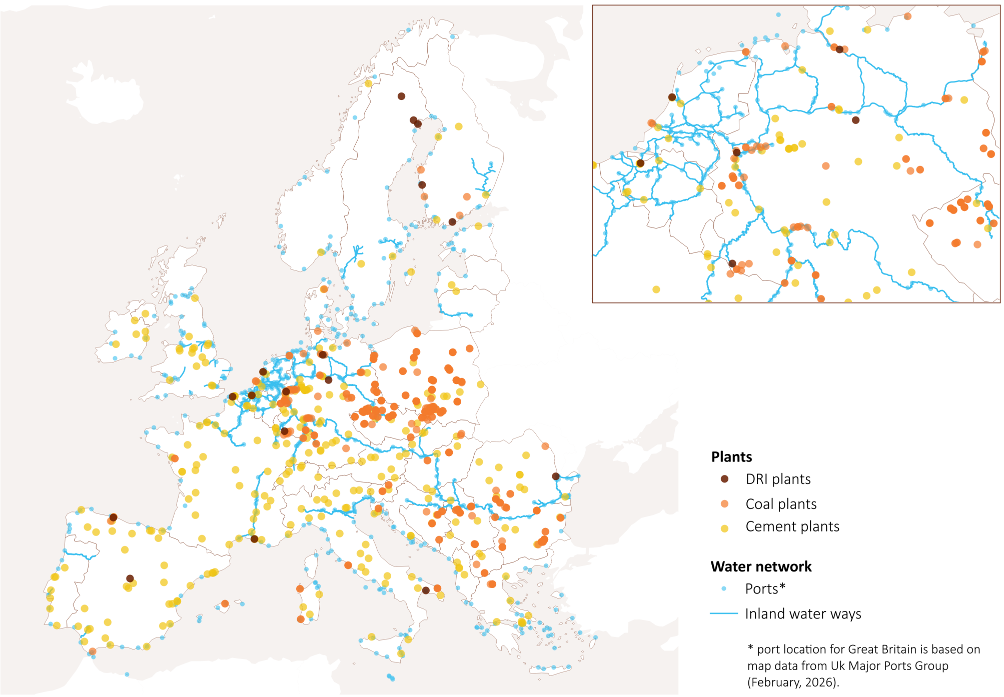


Figure SI3: Means of transport required during summer-autumn for the iron fluxes associated with (a) the direct use of iron in the countries where it is reduced, (b) the electricity-driven scenario, and (c) the heat-driven scenario. In each case, a zoom on Belgium, Netherlands, and Germany is displayed.

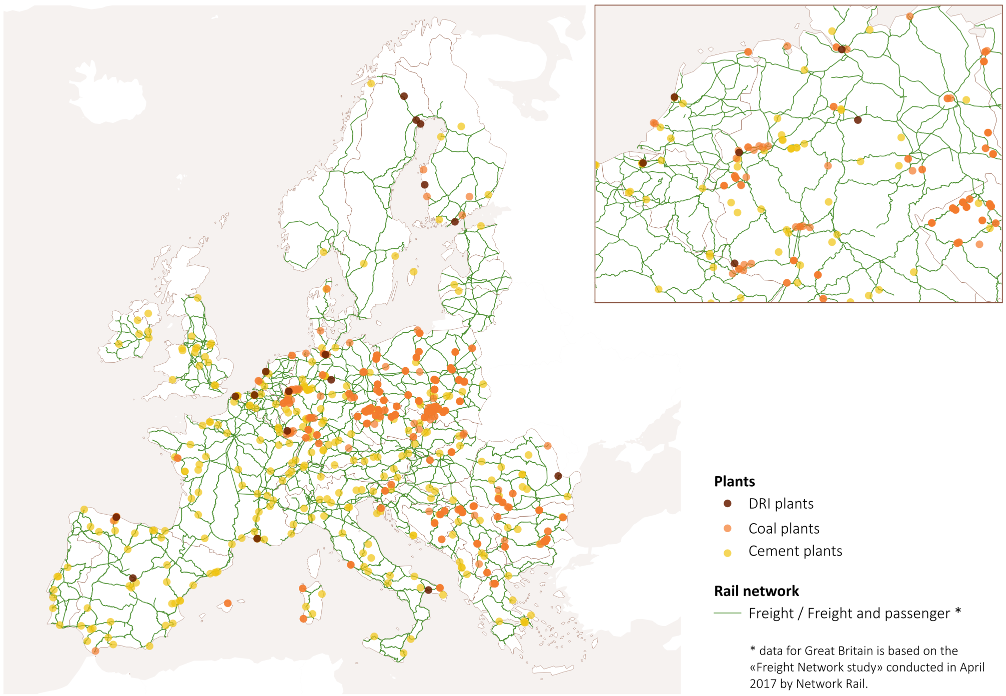
# SI6 - Considered transport network including inland waterways and rail freight

As the three considered transport means include sea shipping, inland waterways, and rail freight, the considered transport infrastructure between plants was considered. It is illustrated in Figure SI4 and in Figure SI5 for inland waterways and railway freight, respectively. The network is based on European Commission data [4] and complementary sources [5–7], considering only double-track and industrial rail lines to the plants [8].



* port location for Great Britain is based on map data from Uk Major Ports Group (February, 2026).

Figure SI4: Inland waterways transport network and considered plants.



* data for Great Britain is based on the «Freight Network study» conducted in April 2017 by Network Rail.

Figure SI5: Rail freight transport network and considered plants.

# References

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