WHAT CONTRIBUTION COULD INDUSTRIAL SYMBIOSIS MAKE TO MITIGATING INDUSTRIAL GREENHOUSE GAS (GHG) EMISSIONS IN BULK MATERIAL PRODUCTION?

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1 Material flow charts

The process flow charts in the following sections represent the stylised production routes for assessing the industrial symbiosis potential. Each process is represented with a box and the main output flow is visualised with a circle. The processes which only operate in the two scenarios of industrial symbiosis are highlighted with colours: orange for processes operating in both scenarios and green for those added only in scenario B (full symbiosis).

1.1 Steel production

The process route for the blast furnace steel production used in the model is depicted in Figure S1.

Figure S1: Process chart of BF steel production in the model
The process route for the electric arc furnace steel production used in the model is depicted in Figure S 2.

**Figure S 2: Process chart of EAF steel production in the model**
1.2 Cement production

The process route for the integrated cement production used in the model is depicted in Figure S 3.

**Figure S 3: Process chart of cement production in the model**
1.3 Aluminium production

The process route for the aluminium production used in the model is depicted in Figure S 4.

Figure S 4: Process chart of primary aluminium production in the model
Figure S 5: Process chart of secondary aluminium production in the model
1.4 Pulp and paper production

The process route for the primary paper production used in the model are summarised in Figure S 6 and secondary route in Figure S 7.

Figure S 6: Process chart of primary paper production in the model
Figure S 7: Process chart of paper production in the model
2 Process recipes

The production recipes of the processes used in the model are summarised in this section in tables with material flows and further information. The production recipes were used for the production coefficient matrix for the production system.

The production processes were divided in four categories:

1. Main industrial processes: the main bulk material production processes and the processes that produce the inputs of them.
2. Energy processes for providing heat and electricity: processes for steam and electricity generation.
3. Industrial symbiosis processes for preparing materials for utilisation and combustion: processes that turn one by-product into a usable input of another process.
4. Processes for providing resources from nature and utilising by-products from industry: extraction processes (e.g. mining) and processes in other industries (e.g. chemicals), that provide the inputs needed for the major bulk material production processes.

During the data and literature review, the production recipes were collected for all major processes and sub-processes. The main industrial processes consist of several sub-processes which are summarised in the first section of this supplementary information. The sub-processes provide all inputs required for producing the final material along the process chain. The key parameters are summarised in Table S 1.

Table S 1: Parameters of the production recipes

| Name            | Label             | Example  | Description                                                  |
|-----------------|-------------------|----------|--------------------------------------------------------------|
| Flow            | stream_title      | "Iron"   | Name of the physical flow, e.g. "BF_Iron".                 |
| Temperature     | temperature       | 300°C    | Temperature of the flow in °C; hot flows can be used in heat exchangers. |
| Coefficient     | avg_coefficient   | 0.1      | Production coefficient for the given process, e.g. 0.1 kg/kg output. |
| Unit            | stream_unit       | kg/kg, kWh/kg | All physical flows are reported in kg/kg; kWh is used for electricity and MJ/kg for heat demand. |
| Direction       | stream_direction  | Input or output | Production coefficient is negative for inputs and positive for outputs. |
| Coefficient     | avg_recipe_source | 0.1      | Reference(s) for the production recipes; see Table S 4 for detailed overview. |
| Reference       | source            | Author (Year) |                                                      |
| Comment         | comment           | Text and description | Additional information on the stream and calculations. |
The global material production for primary and secondary production in 2017 is used in the model for the global material demand ($y$). It is summarised in Table S 2.

**Table S 2: Global material demand in 2017**

| Material Demand (Mt)          | 2017 | Unit | Source                                      |
|-------------------------------|------|------|---------------------------------------------|
| Blast furnace steel           | 1207 | Mt   | World Steel Association (2018a)             |
| EAF steel                     | 473  | Mt   | World Steel Association (2018a)             |
| Cement                        | 4050 | Mt   | Statista (2019)                             |
| Aluminium (primary)           | 63   | Mt   | World Aluminium (2021)                      |
| Aluminium (from scrap)        | 29   | Mt   | World Aluminium (2021)                      |
| Paper                         | 420  | Mt   | Statista (2020)                             |
| Paper (primary prod.)         | 263  | Mt   | Statista (2020)                             |

The constraints for the availability of scrap and secondary materials used in the model as finite entries in vector $c$ are summarised in Table S 3.

**Table S 3: Constraints of scrap supply**

| Secondary supply              | 2017 | Unit | Source                                          | Comment                                                                 |
|-------------------------------|------|------|------------------------------------------------|-------------------------------------------------------------------------|
| EAF Scrap                     | 555  | Mt   | World Steel Association (2018)                  | Input required for producing 473 Mt EAF steel as input.                 |
| Aluminium Scrap               | 30   | Mt   | World Aluminium (2021)                         | 32% of secondary production.                                            |
| Paper recycling               | 233  | Mt   | FAO (2021)                                     | Global amount of recovered paper in 2017.                               |
| Fly ash                       | 215  | Mt   | IEA (2020), Ritter (2016)                      | IEA (2020) reports a share of 5.3% fly ash in cement in 2019. Using this value for 2017 production: $4050 \text{ Mt} \times 0.053\% = 214.65 \text{ Mt}$ fly ash use for the reference scenario. For the symbiosis scenario, the constraint is removed (up to the maximum available amount of 1000 Mt). |
2.1 Main industrial production processes

The following sections contain the production recipes data tables used in the global production model. Table S 4 summarises the processes and sources used for the production recipes.

Table S 4: Overview of the sources used for the production recipes

| Sector    | Explanation of data used                                                                 | Data sources |
|-----------|------------------------------------------------------------------------------------------|--------------|
| Steel     | Global average flow data for BF steel production and EAF production from a representative set of steel production sites using data from World Steel Association. Additional information from the Best Available Technologies (BAT) documents by the European Commission was used for missing flows. | 5, 6, 7, 8, 9, 10, 11, 12 |
| Cement    | Survey data collected by the GNR initiative and additional information on flows and temperatures from peer-reviewed case studies and technical reports on the use of cementitious materials. | 13, 14, 15, 16, 17, 18, 19 |
| Aluminium | Data on global and European Aluminium flows from the World Aluminium Association and additional information on waste heat recovery potentials from industrial case studies. | 20, 21, 22, 23, 24, 25 |
| Paper     | Process-level data from the BAT documents, two peer-reviewed analyses of the material flows in paper production systems and emissions data from LCI database Ecoinvent. | 26, 27, 28, 29, 30, 31, 32, 12 |

For steel mass flows, the global average steel resource data for BF and EAF steel production from Gonzalez Hernandez et al.6 was used. The flow and temperature information in McBrien et al.5 was used for the blast furnace route of steel production. For electric arc furnaces, the balanced mass flows from Krassnig et al. (2007) were used. Further information on the electricity demand and flows of sensible heat in flue gases from EAF was taken from the BAT documents7 and information on GHG emissions from Pardo and Moya.10

For aluminium production processes, mass flow information was used from Balomenos et al. (2017) and temperature information was taken from Nowicki and Gosselin (2012). The information on by-product flows like bauxite residues were taken from World Aluminium (2020). The BAT document from the European Commission22 was used for a simplified reference process for secondary aluminium production.

For cement production, the data for global average production and its inputs was taken from GNR (2017) and two further processes with a higher intake of cementitious materials (fly ash and slags) were added based on the processes described in Scrivener et al. (2016) and blended cements used in Huntzinger and Eatmon (2009). Information on clinker mass balances and temperature levels of the flows for heat recovery was taken from Gao et al. (2016).

The mass flows for paper production were taken from the BAT28, the life-cycle inventory in Corcelli et al.26 and for paper recycling from Christensen and Damgaard.27 The GHG emissions factors were taken from the BAT documents and for pulp production from the data provided in the Ecoinvent database.29
### 2.1.1 Steel production

**Table S 5: Production recipe for coking**

| stream_title  | T     | avg_coefficient | stream_unit | stream_direction | stream_type |
|--------------|-------|-----------------|-------------|-----------------|-------------|
| Coal         | 1100  | 1.30            | kg/kg       | input           | material    |
| COG          | 1100  | 0.10            | kg/kg       | input           | material    |
| Air          | 1100  | 1.10            | kg/kg       | input           | material    |
| Electricity  |       | 0.08            | kWh/kg      | input           | electricity |
| Coke         | 1100  | 1.00            | kg/kg       | output          | material    |
| COG          | 700   | 0.20            | kg/kg       | output          | material    |
| Tar          | 1100  | 0.10            | kg/kg       | output          | material    |
| Flue gas     | 250   | 1.10            | kg/kg       | output          | material    |
| Other_coking | 1100  | 0.10            | kg/kg       | output          | material    |
| GHG_emissions| 1100  | 0.34            | kg/kg       | output          | GHG         |

**Table S 6: Production recipe for sintering**

| stream_title  | T     | avg_coefficient | stream_unit | stream_direction | stream_type |
|--------------|-------|-----------------|-------------|-----------------|-------------|
| Iron ore     | 1300  | 1.00            | kg/kg       | input           | material    |
| Coke breeze  | 1300  | 0.05            | kg/kg       | input           | material    |
| Combustion Air| 1300  | 0.60            | kg/kg       | input           | material    |
| Electricity  |       | 0.11            | kWh/kg      | input           | material    |
| Sinter       | 700   | 1.00            | kg/kg       | output          | material    |
| Flue gas     | 350   | 0.65            | kg/kg       | output          | material    |
| GHG_emissions|       | 0.20            | kg/kg       | output          | GHG         |

**Table S 7: Production recipe for blast furnace (BF) ironmaking**

| stream_title  | T     | avg_coefficient | stream_unit | stream_direction | stream_type |
|--------------|-------|-----------------|-------------|-----------------|-------------|
| Coke         | 1200  | 0.41            | kg/kg       | input           | material    |
| Coal         | 1200  | 0.10            | kg/kg       | input           | material    |
| Sinter       | 1200  | 1.39            | kg/kg       | input           | material    |
| Air          | 1180  | 1.22            | kg/kg       | input           | material    |
| Natural gas  | 1180  | 0.06            | kg/kg       | input           | material    |
| Electricity  | 0     | 0.03            | kWh/kg      | input           | material    |
| Chemical_energy| 12.30 |               | MJ/kg       | input           | material    |
| Pig iron     | 1500  | 1.00            | kg/kg       | output          | material    |
| BF CO        | 180   | 0.32            | kg/kg       | output          | material    |
| BF CO2       | 180   | 0.32            | kg/kg       | output          | material    |
| BF Gas Other | 180   | 0.96            | kg/kg       | output          | material    |
| Slag         | 1500  | 0.28            | kg/kg       | output          | material    |
| Blast stove exhaust | 250 | 0.21            | kg/kg       | output          | material    |
| Imbalance    |       | 0.04            | kg/kg       | output          | material    |
| GHG_emissions| 1.21  |                | kg/kg       | output          | GHG         |
Table S 8: Production recipe for basic oxygen furnace (BOF) steelmaking

| stream_title     | T    | avg_coefficient | stream_unit | stream_direction | stream_type |
|------------------|------|-----------------|-------------|-----------------|-------------|
| Pig iron         | 1700 | 0.98            | kg/kg       | input           | material    |
| Scrap            | 1700 | 0.09            | kg/kg       | input           | material    |
| Oxygen           | 1700 | 0.07            | kg/kg       | input           | material    |
| Other_steelmaking|      | 0.07            | kg/kg       | input           | material    |
| Electricity      |      | 0.08            | kWh/kg      | input           | electricity |
| BOF exhaust      | 1700 | 0.10            | kg/kg       | output          | material    |
| Slag             | 1700 | 0.13            | kg/kg       | output          | material    |
| Steel            | 1700 | 1.00            | kg/kg       | output          | material    |
| GHG_emissions    |      | 0.18            | kg/kg       | output          | GHG         |

Table S 9: Production recipe for electric arc furnace (EAF) steelmaking

| stream_title    | T    | avg_coefficient | stream_unit | stream_direction | stream_type |
|-----------------|------|-----------------|-------------|-----------------|-------------|
| Limestone       | 25   | 0.05            | kg/kg       | input           | material    |
| Coal            | 25   | 0.01            | kg/kg       | input           | material    |
| Scrap           | 25   | 1.15            | kg/kg       | input           | material    |
| Natural gas     | 25   | 0.05            | kg/kg       | input           | material    |
| Oxygen          | 25   | 0.05            | kg/kg       | input           | material    |
| Electrode       | 25   | 0.02            | kg/kg       | input           | material    |
| Electricity     |      | 0.51            | kWh/kg      | input           | electricity |
| Other input     | 25   | 0.10            | kg/kg       | input           | imbalance   |
| Dust            | 25   | 0.02            | kg/kg       | output          | material    |
| Steel           | 700  | 1.00            | kg/kg       | output          | material    |
| Slag            |      | 0.20            | kg/kg       | output          | material    |
| Flue gas heat   | 1000 | 0.50            | MJ/kg       | output          | energy      |
| CO2             |      | 0.24            | kg/kg       | output          | material    |
| GHG_emissions   |      | 0.24            | kg/kg       | output          | GHG         |
2.1.2 Cement production

The production of cement consists of the processes for raw meal, clinker and cement production.

Table S10: Production recipe for raw meal production

| stream_title              | T  | avg_coefficient | stream_unit | stream_direction | stream_type |
|---------------------------|----|-----------------|-------------|------------------|-------------|
| Air                       | 25 | 1.01            | kg/kg       | input            | material    |
| Limestone                 | 25 | 0.88            | kg/kg       | input            | material    |
| Air to roller crusher     | 25 | 0.35            | kg/kg       | input            | material    |
| Silica input              | 25 | 0.06            | kg/kg       | input            | material    |
| Leaking air               | 25 | 0.06            | kg/kg       | input            | material    |
| Air to dust collection    | 25 | 0.03            | kg/kg       | input            | material    |
| Iron ore                  | 25 | 0.02            | kg/kg       | input            | material    |
| Clay input                | 25 | 0.02            | kg/kg       | input            | material    |
| Dust in the gas           | 25 | 0.02            | kg/kg       | input            | material    |
| Moisture                  | 25 | 0.01            | kg/kg       | input            | material    |
| Electricity               |    | 0.04            | kWh/kg      | input            | electricity |
| Flue gas                  | 100| 1.45            | kg/kg       | output           | material    |
| Raw meal                  | 100| 1.00            | kg/kg       | output           | material    |
| Other output              | 100| 0.03            | kg/kg       | output           | material    |
| Moisture in raw meal      | 100| 0.01            | kg/kg       | output           | material    |
| GHG_emissions            |    | 0.03            | kg/kg       | output           | GHG         |
Table S 11: Production recipe for clinker production

| stream_title                  | T | avg_coefficient | stream_unit | stream_direction | stream_type |
|------------------------------|---|-----------------|-------------|-----------------|-------------|
| Raw meal                     |   | 1.56            | kg/kg       | input           | material    |
| Coal for clinker production  |   | 0.13            | kg/kg       | input           | material    |
| Heat requirement             |   | 3.50            | MJ/kg       | input           | energy      |
| Primary air into the kiln    |   | 0.05            | kg/kg       | input           | material    |
| Air into kiln with coal      |   | 0.02            | kg/kg       | input           | material    |
| Air into calciner with coal  |   | 0.04            | kg/kg       | input           | material    |
| Air into cooler              |   | 2.33            | kg/kg       | input           | material    |
| Air leaking into the kiln system | | 0.56 | kg/kg | input | material |
| Clinker                      |   | 1.00            | kg/kg       | output          | material    |
| Waste gas from pre-heater   | 380 | 1.92           | kg/kg       | output          | material    |
| CKD from pre-heater waste gas | | 0.10 | kg/kg | output | material |
| Flue gas from clinker cooler to WHRSG | 360 | 1.06 | kg/kg | output | material |
| Low temperature flue gas to WHRSG from cooler | | 0.40 | kg/kg | output | material |
| Flue gas from cooler to coal mill | | 0.14 | kg/kg | output | material |
| CKD from cooler high temperature gas | | 0.01 | kg/kg | output | material |
| Other output                 |   | 0.06            | kg/kg       | output          | material    |
| Calcination emissions        |   | 0.55            | kg/kg       | output          | material    |
| Fuel emissions               |   | 0.30            | kg/kg       | output          | material    |
| GHG_emissions                |   | 0.84            | kg/kg       | output          | GHG         |

Table S 12: Production recipe for average cement production

| stream_title                  | T | avg_coefficient | stream_unit | stream_direction | stream_type |
|------------------------------|---|-----------------|-------------|-----------------|-------------|
| Limestone                    |   | 0.06            | kg/kg       | input           | material    |
| Natural Pozzolana            |   | 0.02            | kg/kg       | input           | material    |
| Air                          |   | 2.41            | kg/kg       | input           | material    |
| Natural gas                  |   | 0.05            | kg/kg       | input           | material    |
| Slag                         |   | 0.10            | kg/kg       | input           | material    |
| Fly ash                      |   | 0.04            | kg/kg       | input           | material    |
| Moisture                     |   | 0.01            | kg/kg       | input           | material    |
| Clinker                      |   | 0.84            | kg/kg       | input           | material    |
| Gypsum                       |   | 0.04            | kg/kg       | input           | material    |
| Electricity                  |   | 0.09            | kWh/kg      | input           | electricity |
| Gas from separator dust collector | 1.94 | kg/kg | output | material |
| Gas from mill dust collector |   | 0.46            | kg/kg       | output          | material    |
| Cement                       |   | 1.00            | kg/kg       | output          | material    |
| Other output                 |   | 0.16            | kg/kg       | output          | material    |
| GHG_emissions                |   | 0.20            | kg/kg       | output          | GHG         |
2.1.3 Aluminium production

For aluminium production, the data provided by World Aluminium\textsuperscript{33} and World Aluminium\textsuperscript{34} was used for the major mass flows. The production data was extended with the input-balances provided by European Commission\textsuperscript{22} and case studies of aluminium production by Balomenos et al.\textsuperscript{35}

Table S 13: Production recipe for alumina

| stream_title       | T  | avg_coefficient | stream_unit | stream_direction | stream_type |
|--------------------|----|-----------------|-------------|------------------|-------------|
| Bauxite            | 25 | 2.40            | kg/kg       | input            | material    |
| NaOH               | 25 | 0.05            | kg/kg       | input            | material    |
| Limestone          | 25 | 0.03            | kg/kg       | input            | material    |
| Other input        | 25 | 0.93            | kg/kg       | input            | imbalance   |
| Water              | 25 | 6.00            | kg/kg       | input            | material    |
| Electricity        |    | 0.20            | kWh/kg      | input            | electricity |
| Diesel fuel        | 25 | 0.28            | kg/kg       | input            | material    |
| Red mud            | 180| 1.00            | kg/kg       | output           | material    |
| Water              | 40 | 6.00            | kg/kg       | output           | material    |
| Steam              | 180| 0.86            | kg/kg       | output           | material    |
| CO2                | 180| 0.83            | kg/kg       | output           | material    |
| Alumina            | 180| 1.00            | kg/kg       | output           | material    |
| GHG_emissions      |    | 0.83            | kg/kg       | output           | GHG         |

Table S 14: Production recipe for aluminium

| stream_title         | T   | avg_coefficient | stream_unit | stream_direction | stream_type |
|----------------------|-----|-----------------|-------------|------------------|-------------|
| Alumina              | 1.93| kg/kg           | input       | material         |
| Carbon Anodes        | 0.45| kg/kg           | input       | material         |
| Bath material        | 0.07| kg/kg           | input       | material         |
| Electricity          | 14.80| kWh/kg         | input       | energy           |
| Other input          | 0.06| kg/kg           | input       | material         |
| Aluminium            | 960 | 1.00            | kg/kg       | output           | material    |
| CO2                  | 160 | 1.53            | kg/kg       | output           | material    |
| Waste heat in flue gas| 160| 0.900          | kWh/kg      | output           | material    |
| Spent Pot Lining (SPL)| 960| 0.020          | kg/kg       | output           | material    |
| GHG_emissions        | 4.86| kg/kg           | output      | GHG              |
### Table S 15: Production recipe for aluminium ingot

| stream_title                  | T  | avg_coefficient | stream_unit | stream_direction | stream_type |
|-------------------------------|----|-----------------|-------------|-----------------|-------------|
| Water                         | 25 | 4.25            | kg/kg       | output          | water       |
| Alloy additives               | 25 | 0.02            | kg/kg       | input           | material    |
| Aluminium scraps              | 25 | 0.02            | kg/kg       | input           | material    |
| Remelt ingot                  | 25 | 0.06            | kg/kg       | input           | material    |
| Electricity                   |    | 0.07            | kWh/kg      | input           | electricity |
| Liquid aluminium (from electrolysis) | 960 | 0.94           | kg/kg       | input           | material    |
| Natural gas                   | 25 | 0.03            | kg/kg       | input           | energy      |
| Water                         | 300| 4.20            | kg/kg       | output          | water       |
| Dross                         | 300| 0.02            | kg/kg       | output          | material    |
| Other output                  |    | 0.10            | kg/kg       | output          | material    |
| Aluminium ingot               | 300| 1.00            | kg/kg       | output          | material    |
| GHG_emissions                 |    | 0.13            | kg/kg       | output          | GHG         |

### Table S 16: Production recipe for aluminium ingot from recycling (remelting)

| stream_title                  | T  | avg_coefficient | stream_unit | stream_direction | stream_type |
|-------------------------------|----|-----------------|-------------|-----------------|-------------|
| Aluminium scrap               | 25 | 1.00            | kg/kg       | input           | material    |
| Salt                          | 25 | 0.50            | kg/kg       | input           | material    |
| Other input                   | 25 | 0.07            | kg/kg       | input           | material    |
| Electricity                   |    | 1.50            | kWh/kg      | input           | electricity |
| Heat                          |    | 3.80            | MJ/kg       | input           | energy      |
| Salt slag                     | 25 | 0.50            | kg/kg       | output          | material    |
| Filter dust                   | 25 | 0.03            | kg/kg       | output          | material    |
| Other output                  | 25 | 0.01            | kg/kg       | output          | material    |
| Dross                         | 25 | 0.08            | kg/kg       | output          | material    |
| Aluminium ingot               | 25 | 1.00            | kg/kg       | output          | material    |
| GHG_emissions                 |    | 0.26            | kg/kg       | output          | GHG         |
2.1.4 Paper production

For paper production, a typical tissue mill in the European Union was used as a reference for the energy and mass flows.

Table S 17: Production recipe for pulp making

| stream_title          | T | avg_coefficient | stream_unit | stream_direction | stream_type |
|-----------------------|---|-----------------|-------------|-----------------|-------------|
| Electricity           |   | 0.70            | kWh/kg      | input           | electricity |
| Natural gas (heat)    |   | 0.03            | kg/kg       | input           | material    |
| Steam (heat)          | 400 | 11.7           | MJ/kg       | input           | energy      |
| Oxygen                |   | 0.02            | kg/kg       | input           | material    |
| NaOH                  | 25 | 0.05            | kg/kg       | input           | material    |
| Water (inflow)        | 25 | 7.03            | kg/kg       | input           | material    |
| Wood logs             | 25 | 2.80            | kg/kg       | input           | material    |
| Biomass residues      | 25 | 0.43            | kg/kg       | input           | material    |
| Chemicals for pulping | 25 | 0.08            | kg/kg       | input           | material    |
| Other input           | 25 | 0.04            | kg/kg       | input           | material    |
| Pulp (bleached)       | 25 | 1.00            | kg/kg       | output          | material    |
| Solids                | 25 | 0.01            | kg/kg       | output          | material    |
| Water                 | 25 | 7.39            | kg/kg       | output          | material    |
| Black liquor          | 25 | 1.70            | kg/kg       | output          | material    |
| CO2                   | 25 | 0.34            | kg/kg       | output          | material    |
| GHG_emissions         |   | 0.34            | kg/kg       | output          | GHG         |

Table S 18: Production recipe for paper making

| stream_title          | T | avg_coefficient | stream_unit | stream_direction | stream_type |
|-----------------------|---|-----------------|-------------|-----------------|-------------|
| Electricity           |   | 0.90            | kWh/kg      | input           | electricity |
| Chemicals             |   | 0.05            | kg/kg       | input           | material    |
| Other input           |   | 0.05            | kg/kg       | input           | material    |
| Heat_Steam            |   | 7.73            | MJ/kg       | input           | energy      |
| Heat_Water            |   | 0.24            | MJ/kg       | input           | energy      |
| Heat_Water            |   | 0.12            | MJ/kg       | input           | energy      |
| Pulp                  |   | 1.02            | kg/kg       | input           | material    |
| Paper                 |   | 1.00            | kg/kg       | output          | material    |
| Sludge                |   | 0.12            | kg/kg       | output          | material    |
| Other                 |   | 0.02            | kg/kg       | output          | material    |
| GHG_emissions         |   | 0.00            | kg/kg       | output          | GHG         |
Table S 19: Production recipe for paper from recycling

| stream_title                              | temperat ure | avg_coeffici ent | stream_unit | stream_direction | stream_type |
|-------------------------------------------|--------------|------------------|-------------|------------------|-------------|
| Heat for paper recycling                  | 150          | 10.1             | MJ/kg       | input            | heat        |
| Electricity                               |              | 0.50             | kWh/kg      | input            | electricity |
| Dry wood                                  | 25           | 0.09             | kg/kg       | input            | material    |
| Chemicals for paper production            | 25           | 0.01             | kg/kg       | input            | material    |
| Paper fibre from recycling                | 25           | 1.22             | kg/kg       | input            | material    |
| Paper (recycling route)                   | 25           | 1.00             | kg/kg       | output           | material    |
| Solid waste (from paper recycling)        | 25           | 0.22             | kg/kg       | output           | material    |
| Other output                              | 25           | 0.10             | kg/kg       | output           | material    |
| GHG_emissions                             |              | 0.33             | kg/kg       | output           | GHG         |
2.2 Energy processes

Various processes for electricity generation, heat generation and heat exchange are used in the model. The following sections summarise the key processes and provide references for the values used for the stylised routes.

2.2.1 Electricity generation

There are four major processes for generating electricity. For the electricity generation in the reference scenario, the global average emissions of electricity production (0.475 kg/kWh) is used.

![Electricity generation process diagram]

**Figure S 8: Process for average global electricity generation**

The GHG emissions for the processes were taken from for coal, gas and biomass combustion and summarised in Table S 20.

| Process name                               | GHG emissions (kgCO2/kWh) | Description                                                | Source    |
|--------------------------------------------|---------------------------|------------------------------------------------------------|-----------|
| Global average electricity production      | 0.475                     | Average global carbon footprint from electricity generation | IEA (2019) |
| Electricity generation from gas            | 0.204                     | Average UK carbon footprint from gas-based electricity generation | BEIS (2019) |

Blast furnace flue gas is combusted using the average heating value (2.7-4.0 MJ/Nm³ with 20-28% carbon monoxide and 1-5% hydrogen). It is assumed that all BF flue gas is combusted. The carbon footprint of 643 kg/t was rounded up to 700 kg/t. Overall, the combustion is assumed to generate 0.2 kWh/Nm³ using conventional combustion efficiency of 30% and converting the MJ to kWh.
2.2.2 Steam generation

Industrial boilers are used for generating steam. Typical efficiencies are taken from ETSAP (2010) and Office of Industrial Technology (2000). Table S 21 provides a summary of the processes and their efficiency.

Table S 21: Overview of processes for industrial steam generation used

| Process name                  | Combustion efficiency (%) | Description                                                                 | Source                        |
|-------------------------------|---------------------------|------------------------------------------------------------------------------|-------------------------------|
| Gas boiler                    | 84%                       | The average efficiency of 84% was chosen for steam generation from gas.      | ETSAP (2010), ITEE (2000)    |
| Coal boiler                   | 89%                       | The average efficiency of 89% was chosen for steam generation from coal.     | ETSAP (2010), ITEE (2000)    |
| Black liquor combustion       | 80%                       | The average efficiency of 80% was chosen for steam generation from biomass. It is assumed that steam generation from black liquor (BL) has a similar efficiency. | Paoli and Cullen (2020)41     |

The steam requirement was usually reported in MJ/kg. For the processes, for which a direct steam flow was required, the steam flows were calculated. The data for the steam heat values was used from steam tables in Rogers and Mayhew.42

In the reference scenario without industrial symbiosis, current combustion processes are used for preheating substance flows. In the scenario of industrial symbiosis, further options for heat exchange between processes are added. The preheaters either directly heat up cold substance flows (e.g. through electricity or fuel) or indirectly heat processes through heat transfer from another hot fluid that is cooled down in the heat exchanger. For the heat exchangers in the model, a heat transfer efficiency 76% was used for the heat exchanger networks.43
2.3 Options for industrial symbiosis

How can industrial by-products be used as an input to another process? The processes that prepare and use those by-products are referred to as “processes of industrial symbiosis” in this model. There are several options for industrial symbiosis, which have been applied at different scales across different industrial processes. A literature review of major case studies of industrial symbiosis was used to obtain a database of by-product exchanges and to classify the symbiotic options for the major bulk material production processes.

Table S 22: Overview of the scenarios of industrial symbiosis

|                              | Reference scenario | Scenario A                                      | Scenario B                                      |
|------------------------------|--------------------|------------------------------------------------|------------------------------------------------|
| Material production          | Global material production in 2017. | Production processes for major bulk materials. |                                                  |
| Main processes               |                     |                                                |                                                |
| Auxiliary processes          | Same auxiliary processes for providing the external inputs. |                                                |                                                |
| Minimum production           | Full combustion of black liquor (BL) and blast furnace (BF) gas within the production system. |                                                |                                                |
| Symbiosis processes          |                     |                                                |                                                |
| Use of secondary raw materials and by-products | Based on current (2017) global average intake, e.g. in cement production. Only a few by-product utilisation processes (representing current use). | No constraints on the maximum intake of cementitious materials (given supply constraints). More by-product utilisation processes are operating. | No constraints on the maximum intake of secondary materials. All by-product utilisation processes are operating. |
| Heat exchange and utilisation | Processes for heat recovery are not operating. | Processes for heat recovery are not operating. | All symbiosis processes and options for heat exchange and recovery (ORC turbines) are operating. |

The symbiosis processes include processes for heat recuperation as well as material utilisation for substituting another input. In order to classify the processes, four different categories were used. These categories reflect the degree to which the technologies for by-product exchanges have been developed or applied. The categories are the following:

1) Commercially applied, processes with high technology readiness level (TRL).
2) High TRL, applied in several but not all countries.
3) Pilot projects and case studies of industrial symbiosis.
4) Not currently deployed (e.g. economic constraints) or no information on application available, literature suggests a potential for symbiosis.

The processes in category 1 were used in the reference scenario. The processes in category 2 are included in the symbiosis scenario A and the options in categories 3 and 4 in scenario B.
2.3.1 Utilisation of solid by-products as inputs

Table S 23: Flows and options for industrial symbiosis from the industrial by-products

| Process Name                      | Flow     | Description and Example                                                                 | Example case study |
|-----------------------------------|----------|----------------------------------------------------------------------------------------|--------------------|
| Coal-fired power plant            | Fly ash  | Using fly ash as a clinker substitute in cement production.                              | Chertow (2012)     |
| Mechanical-chemical pulping       | Black liquor | Combustion for electricity and heat (steam) generation                                      | Bajpai (2014)     |
| Ironmaking (Blast Furnace)        | BF slag  | Using BF slag as a clinker substitute in cement production.                                | Chertow (2012)     |
| Steelmaking in BOS                | BOS slag | Using BOS slag as a clinker substitute in cement production.                               | Chertow (2012)     |
| Steelmaking in EAF                | EAF slag | Using EAF slag as a clinker substitute in cement production.                               | Chertow (2012)     |

For the reference scenario, a BF slag intake of 70% is used as a clinker substitute and no EAF slag and dusts, which represents global slag utilisation in 2010. For the scenario of full symbiosis (B), a replacement of clinker with BOS and EAF slag is introduced. The maximum technical use of fly ash in Portland cement (35%) was taken from Hoenig and Twigg (2009). The cement production processes operating in the symbiosis scenarios are summarised in Table S 24.

Table S 24: Cement production for the scenarios with higher slag and fly ash use

| Substance                          | Cement production with BF slag | Cement production with increased use of BF slag and gypsum | Cement production with fly ash |
|------------------------------------|--------------------------------|------------------------------------------------------------|--------------------------------|
| GHG emissions                      | kg/kg                          | 0.05                                                       | 0.05                           |
| Electricity                        | kWh/kg                         | -0.085                                                    | -0.085                         |
| Natural gas                        | kg/kg                          | -0.050                                                    | -0.050                         |
| BF/BOS Slag                        | kg/kg                          | -0.25                                                     | -0.20                          |
| Limestone                          | kg/kg                          | -0.065                                                    | -0.065                         |
| EAF Dust                           | kg/kg                          | -0.10                                                     |                                |
| Moisture                           | kg/kg                          | -0.01                                                     | -0.01                          |
| Clinker                            | kg/kg                          | -0.6                                                      | -0.6                            |
| Fly ash                            | kg/kg                          | -0.035                                                    | -0.30                          |
| Gypsum                             | kg/kg                          | -0.05                                                     | -0.1                            |
| Cement                             | kg/kg                          | 1                                                         | 1                               |
| Pozzolana and other cementitious materials | kg/kg                  | -0.05                                                     |                                |
2.3.2 Waste heat recovery

In the analysis of a global symbiosis, the urban sector is included via heat recovery e.g. in Organic Rankine Cycle turbines in scenario B. The detailed inclusion of the urban sector, i.e. district heating networks was not included due to several reasons: there are practical limitations of implementing these technologies for remote production sites and the overall utilisation potential is dependent on available infrastructure, such as district heating systems which would need to be included in the emissions accounting. Some practical limitations are the following:

- **Timing**: The waste heat availability (“generation” does not necessarily match with the heat demand by households. This is especially important for batch processes, e.g. electric arc furnaces for which steam accumulators are required.\(^{45}\) For periods without heat demand in summer, additional ORC turbines are needed\(^ {46}\) to capture the waste heat.

- **Distance**: The efficiency of heat transport and provision limits the potential demand to areas around industrial clusters: The recommended maximum distance of the pipe infrastructure between heat source and user is between 10 kilometres\(^ {47}\) and 15 kilometres\(^ {48}\) in order to avoid major heat transport losses. Hence, there are three categories of residential buildings which can use the waste heat: (1) new buildings, (2) buildings with decentralised heat generation that can be changed to district heating and (3) buildings already connected to the DH grid. Older buildings, especially Victorian houses, will most likely not profit from the DH since they are not connected to the DH network. Overall, the distance of the generation to the district heating network reduces the overall potential though some first studies estimate that the distance can be increased to a few dozen kilometres.\(^ {49}\) The utilisation of waste heat, however, could assessed in a more detailed geographical analysis of potentials of symbiosis.

- **Large infrastructure investments**: For district heating networks, large infrastructure investments are needed. Current approaches for life-cycle assessment of DH network, does not include emissions of the infrastructure\(^ {50}\). The embodied emissions from the infrastructure are low compared to the potential savings from a more efficient generation\(^ {51}\).

- **Alternatives for heating**: On the heat supply side, other low-carbon technologies compete with heat provided by heat networks and affect its implementation. These are decentralised gas- or biomass-based boilers and electric heat pumps, which could have lower specific emissions than centralised gas- or oil-fired boilers\(^ {52}\).

- **Regulation**: The difficulty of district heating deployment lies in the infrastructural arrangement and contractual design. Bürger et al. (2019) describe the heterogenous institutional set-up of district heating markets and discuss the challenges of transforming district heating grids.

- **Back-up capacities and functional storage**: The availability of back-up capacities for heat generation during production stops (planned and unplanned) as well as provision of heat in intermitting processes (e.g. batch-processes like the EAF) pose further challenges to the operation of DH networks. If planned carefully, the DH networks could be used as a thermal heat storage to balance intermittent renewable electricity using heat accumulators\(^ {54}\). Current design of DH networks, however, allows for only limited flexibility.\(^ {55}\) Hence, gas- or coal-fired power plants would be needed as a back-up capacity to the heat networks. These might then have higher carbon footprints per unit of heat delivered (compared to decentralised heating), reducing the overall efficiency gains through DH networks.

For the recovery of waste heat from hot flue gas streams, Organic Ranking Cycle (ORC) turbine processes were added. These generate electricity from hot flue gases through a primary and secondary steam cycle using various fluids. The typical efficiency the ORC turbine of 15% is used\(^ {56}\). Figure S 9 illustrates a representative and a simplified process design of conversion of hot flue gases to cold flue gases and electricity. The ORC turbines in the model follow the simplified process design.
For some heat recovery processes, data on available processes for heat recovery was available. These reported implementation of heat recovery options in the industrial processes were used for several flows. The processes are summarised in Table S 25 and added to the production system as “symbiosis processes” and operate in scenario B.
| Group           | Process Name                               | Flow            | Description and Example                                                                 | Example case study |
|-----------------|--------------------------------------------|-----------------|----------------------------------------------------------------------------------------|--------------------|
| Aluminium       | Aluminium production waste heat recovery  | Flue gas        | 700°C flue gas converted into air (80°C) and electricity (0.9 kWh/kg).                   | Castelli et al. (2019) |
| Aluminium       | Alumina production waste heat recovery     | Flue gas        | 180°C flue gas stream used for heat recovery in ORC                                     | Castelli et al. (2019) |
| Cement          | Cement production                          | Clinker production flue gas | The ORC turbine added to the clinker production therefore generates 0.045 kWh/kg<sub>clinker</sub> flue gases. | Zhu (2011) |
| Cement          | Clinker production                         | Flue gas        | Heat recovery of hot flue gas from clinker cooler                                       | Cao et al. (2018)  |
| Cement          | Cement production                          | Hot flue gases from clinker preheating | Steam generation from clinker preheater flue gas                                     | Tsiliyannis (2018) |
| Steel           | Sinter waste heat recovery                 | Sinter flue gas | Electricity generation; 0.02 kWh/kg                                                     | Li et al. (2010)   |
| Steel           | Converter flue gas waste heat recovery     | Converter flue gas | Electricity generation; 0.012 kWh/kg                                                   | Li et al. (2010)   |
| Steel           | Ironmaking (Blast stove exhaust)           | Flue gas        | Heat recovery of hot flue gas                                                            | McBrien et al. (2016) |
| Steel           | Converter flue gas waste heat recovery     | Converter flue gas | Waste heat boiler to generate steam from BOF exhaust                                    | McBrien et al. (2016) |
| Steel           | Sinter waste heat recovery                 | Sinter flue gas | Heat recovery of hot flue gas                                                            | McBrien et al. (2016) |
| Steel           | Blast furnace gas (180°C)                  | Flue gas        | Heat recovery of hot flue gas with ORC                                                   | McBrien et al. (2016) |
| Steel           | Ironmaking (Blast stove exhaust) ORC       | Flue gas        | Heat recovery of hot flue gas with ORC                                                   | McBrien et al. (2016) |
| Steel           | Coke oven flue gas recovery                | Coke oven flue gas | Heat recovery                                                                            | McBrien et al. (2016) |
| Steel           | Coke oven flue gas recovery                | Coke oven flue gas | Heat recovery                                                                            | McBrien et al. (2016) |
| Steel           | EAF waste heat recovery                    | EAF waste heat | A waste-heat-recovery boiler can generate electricity offering a 7.5% reduction in EAF energy requirements. | Chan et al. (2019) |
| Steel           | Coke oven tar recovery                     | Coke oven flue gas | Heat recovery                                                                            | McBrien et al. (2016) |
2.3.3 Solid waste as a fuel

The use of solid waste was included in the model as a fuel for cement production using current global average co-incineration of alternative fuels. An example case study using municipal solid waste as a fuel is provided by Hashimoto et al. In that, they use a LCA-based substitution analysis to assess the effect of a fuel switch from coal to municipal solid waste, which have a slightly lower carbon footprint, in four scenarios of symbiosis. The carbon footprint of the fuel use is reduced from 2.58 tCO2/t (coal) to 2.44 tCO2/t (MSW), leading to an overall emissions reduction of around 44ktCO2 per year (10% of the combustion-related emissions).

If biomass fuels or alternative fuels are combusted instead of fossil fuels, the overall emissions might remain constant (or increase) while the fossil-based emissions are reduced. Figure 18 in the report by Hinkel et al. visualises emissions factors and typical biomass content of different alternative fuels and contrasts them with fossil fuels currently used in cement production. The biomass content of typical fuels such as animal meal and sewage fuel is up to 100% with an emission factor of up to 110 kgCO2/GJ. The emissions factor for fossil fuels is significantly lower (55-90 kgCO2/GJ), though these emissions are solely fossil-based. If the emissions accounting from the WBCSD is used, the biomass-based emissions are not allocated to cement production. Additional through MSW combustion were not attributed to the co-incineration since the model does not differentiate between biogenic and fossil-based CO2 emissions.

The analysis in this paper, however, includes all carbon dioxide emissions regardless of their origin (biomass/fossil-based). Hence, the emissions from biomass-based waste are included as normal GHG emission and additional GHG emissions reduction credits were not attributed to the processes. The theoretical potential of GHG emissions reduction reported in Hashimoto et al. considers the biomass-based emissions as emissions savings since they use a LCA-based emissions factor. Hence, they estimate a larger potential for savings due to the fuel switch to MSW.
# 2.4 Summary of the processes in the model

The processes used in the scenarios are summarised in this section. Table S 26 summarises the processes of the production system. For each process, a short description is provided.

## Table S 26: Full list of processes and brief description

| Process name                          | Process name (model)                  | Description                                                                 |
|---------------------------------------|---------------------------------------|----------------------------------------------------------------------------|
| Coking                                | st_coking                             | Produces coke required for BF steel production                              |
| Sintering                             | st_sintering                          | Produces sinter required for BF steel production                            |
| Ironmaking (Blast Furnace)            | st_bf_ironmaking                      | Produces liquid iron for steelmaking                                        |
| Ironmaking (Blast Furnace)            | st_bf_ironmaking t2                   | Produces liquid iron for steelmaking (with top-gas circulation)             |
| Steelmaking (BOS)                     | st_bos_steelmaking                    | BOS Steelmaking for steel                                                  |
| Overall steel production via BF route | st_bf_steel_total                     | Overall BF steel (from different production routes)                         |
| Steelmaking (EAF)                     | st_eaf_steelmaking                    | EAF ironmaking for EAF steel                                               |
| Steelmaking (EAF) with heat recovery  | st_eaf_steelmaking s20                | EAF ironmaking for EAF steel with more efficient process                    |
| Overall steel production via EAF route| st_eaf_steel_total                    | Overall EAF steel (from different production routes)                        |
| Electricity generation (BF steel)     | st_el_steel_bf                        | Provides electricity for BF/BOS steel production                            |
| Electricity generation (EAF steel)    | st_el_steel_eaf                       | Provides electricity for EAF                                               |
| Sinter heating                        | st_sinter_heating                     | Heating sinter for use in BF                                               |
| Iron heating                          | st_iron_heating_fuels                 | Heats iron for steelmaking process                                          |
| Scrap cooling                         | st_bf_cooling_scrap                   | Cooling scrap from BF route                                                |
| Raw meal production in raw mill       | ce_raw_mill                           | Produces raw meal for clinker production                                    |
| Clinker production                    | ce_clinker_production                 | Produces clinker for cement production                                     |
| Clinker production (T2)               | ce_clinker_production t2              | Produces clinker for cement production                                     |
| Cement Production (Global Average)    | ce_cement_production_global_avg       | Global average cement production based on GNR data                          |
| Cement Production (T1)                | ce_cement_production_s30              | Cement production process with by-product use 1                             |
| Cement Production (T2)                | ce_cement_production_s31              | Cement production process with by-product use 2                             |
| Cement Production (T3)                | ce_cement_production_s32              | Cement production process with by-product use 3                             |
| Preparation of clinker for cement (heating) | ce_clinker_preparation_for_cement | Overall cement production                                                  |
| Overall cement production             | ce_total_cement_production            | Prepares clinker for use in cement production                               |
| Electricity generation (cement)       | ce_el_cement                          | Provides electricity for cement production                                 |
| Alumina production                    | al_alumina_production                 | Produces alumina from bauxite                                              |
| Aluminium electrolysis                | al_aluminium_electrolysis             | Produces liquid aluminium from alumina                                     |
| Ingot casting                         | al_aluminium_ingot                    | Casting aluminium ingots from aluminium                                    |
| Aluminium heating                     | al_aluminium_heating                  | Heating aluminium for casting                                              |
| Aluminium cooling                     | al_aluminium_cooling                  | Process for cooling hot aluminium                                          |
| Process name                        | Process name (model)                                | Description                                                                 |
|------------------------------------|----------------------------------------------------|-----------------------------------------------------------------------------|
| Aluminium remelting ingot scrap    | al_aluminium_remelt_ingot_scrap                    | Provides Aluminium scrap for electrolysis                                    |
| Aluminium recycling                | al_aluminium_recycling                             | Process for recycling aluminium (remelting)                                 |
| Electricity generation (aluminium) | al_el_aluminium                                    | Provides electricity for aluminium production                              |
| Mechanical pulping                 | pp_pulp_mech_chem                                  | Mechanical and chemical pulping process for paper production                |
| Chemical pulping                   | pp_paper_recycling                                 | Paper recycling processes                                                  |
| Heat provision for paper production| pp_heat_paper_recycling                            | Provides heat/steam for paper production                                    |
| Papermaking production             | pp_paper_primary_route_making                      | Heat provision for paper recycling                                         |
| Global paper demand                | pp_paper_demand                                    | Global paper demand                                                         |
| Primary paper production           | pp_paper_primary                                   | Overall primary paper production via primary route                          |
| Paper recovery                      | pp_paper_secondary                                 | Uses pulp for producing paper                                              |
| Electricity generation (paper)     | pp_el_paper                                        | Electricity generation for paper production                                 |
| Electricity generation             | pp_el_paper_co_generation                          | Electricity generation from biomass combustion                              |
| Combustion of black liquor         | pp_paper_black_liquor_combustion_s51              | Combustion of black liquor                                                 |
| Electricity generation from global average | en_el_global_avg                                  | Average carbon footprint of global electricity generation                    |
| Electricity generation from coal   | en_el_coal                                         | Generates electricity from coal                                             |
| Electricity generation from gas    | en_el_gas                                          | Generates electricity from gas                                              |
| Electricity generation from BF gas combustion | en_el_bf_combustion | Generates electricity from combusting BF gas                               |
| Preheating of air                  | st_heat_preheating                                 | Preheating process for air                                                  |
| Heat provision from natural gas    | st_heat_gen_gas                                    | Hot flue gas / steam from natural gas combustion                            |
| Steam generation from coal         | pp_heat_gen_coal                                   | Hot flue gas / steam from coal combustion                                   |
| Steam generation from gas          | pp_heat_gen_gas                                    | Hot flue gas / steam from natural gas combustion                            |
| Steam generation from biomass      | pp_heat_gen_biomass                                | Hot flue gas / steam from biomass combustion                                |
| Steam generation                   | pp_steam_paper1                                   | Provides steam/heat for paper production                                    |
| Steam generation                   | pp_steam_paper2                                   | Provides steam/heat for paper production                                    |
| Steam generation                   | pp_steam_paper3                                   | Paper production steam proviso with hot flue gas streams from other processes |
| Heat provision for cement          | cem_heat                                           | Heat provision for cement production                                        |
| Heat provision from coal (CEM)     | cem_heat_gen_coal                                  | Provides steam/heat from coal                                              |
| Heat provision from natural gas (CEM) | cem_heat_gen_gas                               | Provides steam/heat from gas                                               |
| Heat provision from coal           | al_heat_gen_coal                                   | Provides steam/heat from coal                                              |
| Heat provision from natural gas    | al_heat_gen_gas                                    | Provides steam/heat from gas                                               |
| Process name                              | Process name (model)                   | Description                                                                 |
|------------------------------------------|----------------------------------------|-----------------------------------------------------------------------------|
| Heat provision from coal                 | en_heat_gen_coal                       | Provides steam/heat from coal                                              |
| Heat provision from natural gas          | en_heat_gen_gas                        | Provides steam/heat from gas                                               |
| Heat generation from biomass             | en_heat_gen_biomass                    | Provides steam/heat from biomass                                           |
| Heat generation from coal                | en_coal_combustion_flue_gas           | Hot flue gas / steam from coal combustion                                  |
| Heat generation from coal gas            | en_gas_combustion_flue_gas            | Hot flue gas / steam from natural gas combustion                            |
| Heat generation from biomass             | en_biomass_combustion_flue_gas        | Hot flue gas / steam from biomass                                          |
| Flue gas heat recovery (to 40°C)         | en_air_cooling                         | Cooling hot flue gases before emitting to atmosphere                       |
| Coal preparation for combustion          | en_coal_preparation_combustion        | Preparation of coal for combustion                                         |
| Heat from gas                            | en_gas_other                          | Heat provision from gas                                                   |
| Gas for ironmaking                       | st_gas_ironmaking                     | Provision of natural gas for ironmaking                                    |
| Preparation of iron ore                 | st_preparation_iron_ore               | Preparation of iron ore for sintering                                      |
| Provision of coke breeze from coke      | st_coke_to_coke_breeze                | Provides coke for coke breeze in steel production                          |
| Production of EAF electrodes            | st_eaf_electrodes                     | Provides EAF electrodes                                                    |
| Scrap heating                            | st_eaf_steel_scrap_heating            | Heating of scrap                                                          |
| Coke oven gas combustion                 | st_coke_oven_gas                      | Combustion of coke oven gas (COG)                                         |
| Air provision                            | st_provision_coke_oven                 | Provision of combustion air for coke oven                                  |
| Preheating process ironmaking            | st_air_preheating_ironmaking          | Preheating process for air in ironmaking                                   |
| Oxygen provision steelmaking             | st_oxygen_provision_steelmaking       | Oxygen provision for steelmaking                                           |
| Oxygen provision ironmaking              | st_oxygen_provision_ironmaking         | Oxygen provision for ironmaking                                           |
| Steel production imbalances              | st_imbalance                           | Imbalance from steel production                                            |
| Air provision                            | ce_air_cement                          | Provision of air for cement production                                     |
| Diesel fuel for clinker production       | ce_fuel_clinker                       | Provision of coke for clinker production from coal. The emission factor used is 0.14 kgCO2/kgCoke (from coal) |
| Air provision                            | ce_gas_cement                          | Air provision for cement                                                   |
| Air provision                            | ce_air_raw_mill                        | Air provision for raw mill                                                |
| Cement production moisture and dust      | ce_raw_mill_moisture_dust              | Moisture and dust from cement production                                  |
| Air provision                            | ce_air_provision_roller_crusher        | Air provision for roller crusher                                          |
| Air provision                            | ce_air_provision_leaking_air           | Air provision                                                             |
| Air provision                            | ce_air_provision_dust_collector        | Air provision                                                             |
| Raw mill moisture and dust               | ce_air_provision_cooler                | Air provision                                                             |
| Air provision                            | ce_air_provision_kiln_system           | Air provision                                                             |
| Imbalance aluminium production           | al_imbalance                           | Aluminium production imbalance                                             |
| Scrap provision for aluminium recycling  | al_aluminium_recycling_scrap          | Provides Aluminium scrap for electrolysis                                  |
| Process name                  | Process name (model)                        | Description                                           |
|------------------------------|---------------------------------------------|-------------------------------------------------------|
| Aluminium dross provision    | al_al_dross                                 | Provision of aluminium dross                          |
| Water provision for alumina  | al_water_provision_alumina                  | Water provision for alumina production               |
| Provision of diesel fuel     | al_diesel_fuel_alumina                      | Provision of diesel for alumina production            |
| Diesel provision for aluminium | al_diesel_fuel_for_aluminium               | Provision of diesel for aluminium production         |
| Mining of iron ore           | ext_minning_iron_ore                        | Mining process extracts iron ore                      |
| Mining of limestone          | ext_minning_limestone                       | Mining process extracts limestone                     |
| Mining of silica             | ext_minning_silica                          | Mining process extracts silica                        |
| Mining of clay               | ext_minning_clay                            | Mining process extracts clay                          |
| Mining of gypsum             | ext_minning_gypsum                          | Mining process extracts gypsum                        |
| Mining of pozzolana          | ext_minning_pozzolana                       | Mining process extracts pozzolana                     |
| Mining of bauxite            | ext_bauxite_mining                          | Mining process extracts mining                        |
| Dust from industrial waste   | ext_waste_management_dust                   | Dust from industrial waste                            |
| Fly ash from industrial waste| ext_waste_management_fly_ash                | Fly ash from industrial waste                         |
| Coal extraction              | ext_coal_extraction                         | Coal extraction                                       |
| Diesel fuel provision        | ext_diesel_fuel                             | Diesel fuel provision                                 |
| Provision of wood logs       | ext_wood_logs                               | Provision of wood logs                                |
| Natural gas extraction       | ext_natural_gas_extraction                  | Natural gas extraction                                |
| Aluminium: production of carbon anodes | ext_aluminium_carbon_anodes                | Aluminium: production of carbon anodes                |
| Aluminium: production of bath material | ext_aluminium_bath_material               | Aluminium: production of bath material                |
| Aluminium: production of argon | ext_aluminium_argon                        | Aluminium: production of argon                        |
| Aluminium: production of alloy additives | ext_alloy_additives                      | Aluminium: production of alloy additives              |
| Biomass provision for pulping | ext_air_provision                          | Biomass provision for pulping                         |
| Provision of air             | ext_provision_combustion_air                | Provision of air                                      |
| Provision of biomass and wood for pulping | ext_biomass_provision_pulping             | Provision of biomass and wood for pulping             |
| Provision of chemicals for pulping | ext_chemical_provisions_pulping            | Provision of chemicals for pulping                    |
| Provision of chemicals (NaOH) | ext_chemicals_provision_NaOH               | Provision of chemicals (NaOH)                        |
| Provision of chemicals for other processes | ext_chemicals_other                      | Provision of chemicals for other processes            |
| Provision of other inputs for paper production | ext_paper_other                       | Provision of other inputs for paper production        |
| Paper collection for recycling | ext_paper_collection_recycling             | Paper collection for recycling                        |
| Water provision              | ext_water_provision                         | Water provision                                       |
| Scrap provision for EAF      | ext_scrap_eaf_provision                     | Scrap provision for EAF                               |
| Air provision                | ext_other_air_provision                     | Air provision                                         |
| Slag cooling                 | hx_slag_cooling1                            | Slag cooling                                          |
| Slag cooling                 | hx_slag_cooling2                            | Slag cooling                                          |
| Slag cooling                 | hx_slag_cooling3                            | Slag cooling                                          |
| Slag cooling with heat exchange | hx_slag_cooling1                           | Cooling slag from steel production with waste heat recovery |
| Process name                      | Process name (model)                                      | Description                                                                 |
|----------------------------------|----------------------------------------------------------|-----------------------------------------------------------------------------|
| Slag cooling with heat exchange  | hx_slag_cooling2                                         | Cooling slag from steel production with waste heat recovery                 |
| Slag cooling with heat exchange  | hx_slag_cooling3                                         | Cooling slag from steel production with waste heat recovery                 |
| Coking tar HX                    | hx_coking_tar                                            | Cooling of tar                                                              |
| Sinter flue gas HX               | hx_sinter_flue_gas_s11                                   | Sinter flue gas recovery                                                    |
| Coking flue gas HX               | hx_blast_stove_steelmaking_s12                           | Blast stove flue gas recovery                                               |
| Ironmaking HX                    | hx_ironmaking_s13                                        | Ironmaking flue gas recovery                                                |
| Blast stove flue gas HX          | hx_blast_stove_steelmaking_s14                           | Blast stove steelmaking recovery in ORC                                     |
| Sinter flue gas HX               | hx_sinter_flue_gas_s15                                   | Sinter flue gas recovery                                                    |
| BF gas HX                        | hx_bf_gas_other_s16                                      | Blast furnace gas                                                           |
| Ironmaking HX                    | hx_ironmaking_s17                                        | Ironmaking flue gas recovery                                                |
| Coke oven flue gas HX            | hx_cooling_coke_oven_s18                                 | Coke oven heat recovery                                                     |
| Coke oven flue gas ORC           | hx_cooling_coke_oven_s19                                 | Coke oven heat recovery                                                     |
| Blast furnace gas                | hx_bf_gas_other                                          | Blast furnace gas                                                           |
| Clinker cooler flue gas ORC      | hx_clinker_cooler_gas_s34                                | Clinker cooler gas heat recovery                                            |
| Clinker preheater gas ORC        | hx_clinker_preheater_gas_s35                             | Clinker preheater gas heat recovery                                         |
| Clinker preheater flue gas HX    | hx_clinker_preheater_gas_s36                             | Clinker preheater gas heat recovery                                         |
| Aluminium flue gas recovery      | hx_aluminium_flue_gas                                    | Aluminium flue gas                                                          |
| Aluminium flue gas recovery      | hx_aluminium_flue_gas_s41                                | Aluminium flue gas heat recovery                                            |
| Coking tar HX                    | hx_coking_tar_s61                                        | Coking tar heat exchange                                                    |
| Coal preheating HX               | hx_coal_preheating                                       | Coal preheating                                                             |
| Air preheating HX                | hx_air_preheating                                        | Air preheating                                                              |
| Flue gas HX/ORC                  | hx_steam_electricity_ORC                                 | Flue gas heat recovery                                                      |
| Provision of other inputs        | other_provision                                          | Other provision of inputs of the production processes                      |
3 Model implementation

This section provides a description of the model and the implementation in python. Figure S 10 summarises the input files and code used for the industrial symbiosis model. The input files are the material demand, symbiosis scenarios and the production coefficient matrix.

Figure S 10: Overview of the model in python

For the model implementation in python (version 3.9.6), the mathematical programming package scipy (version 1.1.0) is used.

Optimisation of production rates uses the function linear program (linprog) in scipy:

```python
optimise_scenario_ref = linprog(parameters_scenario_ref["ghg"],
A_ub=parameters_scenario_ref["A_ub"], b_ub=parameters_scenario_ref["b_ub"],
bounds=parameters_scenario_ref["bounds"], method=optimisation_setup["method"],
options=optimisation_setup["options"])
```
4 Sensitivity analysis

The goal of the uncertainty and sensitivity analysis is to assess the robustness of the symbiosis model with regard to changes in the input parameters. The global symbiosis model has several input parameters which influence the overall system’s GHG emissions. The material demand, the production-coefficients, the process-level GHG emissions and the supply constraints are externally defined. Whereas the production coefficient matrix contains the constant production coefficients (recipes), the other three main parameters can be varied to assess the sensitivity and stability of the model results.

- The global material demand (\( y \)),
- The process-specific GHG emissions (\( g_i \)),
- The supply constraints, i.e. process rates of the external processes that provide fly ash or secondary resources (\( c_i \)).

The sensitivity analysis was conducted (1) for the process-specific GHG emissions and (2) for the constraints on the external supply of fly ash.

Changes in the process-specific GHG emissions

The process-specific GHG emissions (\( g_i \)) include the direct process-level GHG emissions of every production process included in the model. The indirect emissions are covered through the energy inputs (e.g. electricity) of the processes with a process-specific GHG emission factor. The coefficients for the direct emissions for the major bulk material processes were obtained from the literature review. The values (\( g_i \)) were varied by \( \pm 10\% \) and \( \pm 20\% \) for every process. The findings are summarised in Figure S 11 and Figure S 12.

![Figure S 11: Results for changes in emission factors of the processes](image)
The relative changes of the GHG emissions in the reference scenario are consistent with an increase or decrease of the specific emissions factors. Further research could include a more detailed range and uncertainty reporting of the process-level GHG emissions to explicitly include uncertainty in the GHG emission factors as well as the production coefficients.

Fly ash supply
The emissions reductions in cement production mainly stem from the utilisation of fly ash as a cementitious material (with up to 35% use of fly ash). The cement sector emissions reductions (17%) in scenario A are mainly driven by the utilisation of fly ash. Figure S 13 visualises the impact of increasing fly ash supply on the sectoral GHG emissions in cement production for different levels of fly ash supply.

Overall, the relative changes of overall emissions due to changes of the process-level emission factors lead to a similar increases and reductions in system GHG emissions across all scenarios. The changes in the availability of the secondary materials lead to (small) changes in the overall emissions in the reference scenario. Further research could include a more detailed assessment of changes and uncertainty of the production coefficient matrix.
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