

SUPPORTING INFORMATION FOR:

Noori, S., Korevaar, G., Stikkelman, R., & Ramírez, A. (2022.) Exploring the emergence of waste recovery and exchange in industrial clusters. *Journal of Industrial Ecology.*



This supporting information provides a brief description about Linny-R software and its functionalities in cluster modeling. Moreover, it presents technical and economic input data to Linny-R models generated in this work.



# Appendix A: Linny-R and industrial symbiosis modeling

The challenge of required technical and economic details for system-level analysis of industrial plants led to the development of Linny-R software. Process modeling tools cannot take into account the non-technical variables in actors’ decision-making, and Agent-based models are incapable of finding an optimal operating condition of the system. Linny-R is a diagram-based modeling tool for analyzing and optimizing the performance of systems composed of multiple processes and their input/output products, developed by Pieter Bots at Delft University of Technology (Bots, 2021) to solve MILP problems that incorporate physical and non-physical variables. In Linny-R, physical (e.g., material and energy) and data (e.g., information and monetary) flows are modeled as products. Any activity with inflows and outflows is modeled as a process. Activities such as selling, buying, and contracting, which are crucial in IS collaborations, are regarded as processes. In the model, an activity receives input (physical and data flow) to generate outputs. Note that operating and investment costs associated with each activity are implemented in the model as data flows.

Linny-R visualizes all processes and products in network format. A company can then be modeled as a cluster of processes owned by the same actor. The whole system is referred to as the industrial cluster to avoid confusion. Linny-R maximizes profit or minimizes the cost of the entire industrial cluster subject to system constraints. Linny-R assumes actors’ behavior is rational, not random. Actors make a decision based on their economic benefit considering the system constraints. The constraints (e.g., prices, taxes, and environmental pollution limits) can be defined as the lower bounds, upper bounds, production and consumption rates, and prices. It is possible to apply temporal changes in input data in the form of time series, data sets, or function of other model parameters, then investigate the output variations over time. However, optimizing the industrial cluster’s operation in Linny-R has limitations. Linny-R does not check the material and energy balance. The predecessor to cluster modeling in Linny-R is the technical and institutional study of the cluster. Decision variables in the optimization procedure are the production levels of processes in each time step. Prices, capacities, and production and consumption rates are exogenous variables. Thus, their values and temporal changes have to be determined outside the model, and the solver does not calculate such parameters in each time step by itself.

# Appendix B: model material and energy data

*Table B1 Material and energy consumption and generation rates in different processes in PGSEZ (Noori et al., 2021)*

| Actor | Plant | Product | flow rate | Unit |
| --- | --- | --- | --- | --- |
| SKS | P1 | Pellet | 1.45 | tone/ tone product |
| DRI | 1.00 | tone/ tone product |
| Sludge DRI | 0.05 | tone/ tone product |
| Dust DRI | 0.06 | tone/ tone product |
| EL input | 0.47 | GJ/tone product |
| Natural Gas Feedstock | 0.20 | tone/ tone product |
| Natural Gas | 1.58 | GJ/tone product |
| Waste Heat P1 | 0.71 | GJ/tone product |
| Industrial Water | 1.00 | Nm3/tone product |
| Waste Water | 0.40 | Nm3/tone product |
| HOS | P3 | Pellet | 1.45 | tone/ tone product |
| DRI | 1.00 | tone/ tone product |
| Sludge DRI | 0.06 | tone/ tone product |
| Dust DRI | 0.03 | tone/ tone product |
| EL input | 0.42 | GJ/tone product |
| Natural Gas Feedstock | 0.20 | tone/ tone product |
| Natural Gas | 1.58 | GJ/tone product |
| Waste Heat P3 | 0.75 | GJ/tone product |
| Industrial Water | 1.02 | Nm3/tone product |
| Waste Water | 0.30 | Nm3/tone product |
| SAB | P7 | Pellet | 1.37 | tone/ tone product |
| HBI | 1.00 | tone/ tone product |
| Sludge DRI | 0.02 | tone/ tone product |
| Dust DRI | 0.02 | tone/ tone product |
| EL input | 0.50 | GJ/tone product |
| Natural Gas Feedstock | 0.19 | tone/ tone product |
| Natural Gas | 1.49 | GJ/tone product |
| Waste Heat P7 | 0.72 | GJ/tone product |
| Industrial Water | 1.72 | Nm3/tone product |
| Waste Water | 0.69 | Nm3/tone product |
| SKS | P2 | Scrap | 0.02 | tone/ tone product |
| DRI | 1.26 | tone/ tone product |
| Lime | 0.07 | tone/ tone product |
| Ferroalloys | 0.03 | tone/ tone product |
| Coke | 0.49 | GJ/tone product |
| Billet | 1.00 | tone/ tone product |
| Slag | 0.26 | tone/ tone product |
| Dust SMP | 0.01 | tone/ tone product |
| Sludge SMP | 0.05 | tone/ tone product |
| CCM Loss | 0.02 | tone/ tone product |
| EL input | 2.70 | GJ/tone product |
| Natural Gas | 0.18 | GJ /tone product |
| Waste Heat P2 | 0.47 | GJ/tone product |
| Industrial Water | 1.12 | Nm3/tone product |
| Waste Water | 0.53 | Nm3/tone product |
| HOS | P4 | Scrap | 0.03 | tone/ tone product |
| DRI | 1.23 | tone/ tone product |
| Lime | 0.06 | tone/ tone product |
| Ferroalloys | 0.05 | tone/ tone product |
| Coke | 0.20 | GJ /tone product |
| Slab | 1.00 | tone/ tone product |
| Slag | 0.26 | tone/ tone product |
| Dust SMP | 0.01 | tone/ tone product |
| Sludge SMP | 0.08 | tone/ tone product |
| CCM Loss | 0.02 | tone/ tone product |
| EL input | 2.76 | GJ /tone product |
| Natural Gas | 0.11 | GJ /tone product |
| Waste Heat P4 | 0.34 | GJ /tone product |
| Industrial Water | 0.93 | Nm3/tone product |
| Waste Water | 0.53 | Nm3/tone product |
| AAC | P8 | Calcined Coke (CPC) | 0.60 | tone/ tone product |
| Pitch (CTC) | 0.15 | tone/ tone product |
| Spent Anode | 0.25 | tone/ tone product |
| Anode | 1.00 | tone/ tone product |
| Natural Gas | 2.45 | GJ /tone product |
| EL input | 0.50 | GJ /tone product |
| Waste Heat P8 | 0.56 | GJ /tone product |
| AAC | P9 | Alumina | 1.96 | tone/ tone product |
| Cryolite | 0.03 | tone/ tone product |
| Aluminum fluoride | 0.04 | tone/ tone product |
| Anode | 0.45 | tone/ tone product |
| Aluminum ingot | 1.00 | tone/ tone product |
| SPL | 0.02 | tone/ tone product |
| EL input | 56.88 | GJ /tone product |
| Waste Heat P9 | 11.38 | GJ /tone product |
| HOS | P5 | Lime | 0.02 | tone/ tone product |
| Molasses | 0.04 | tone/ tone product |
| CBI | 1.00 | tone/ tone product |
| EL input | 0.06 | GJ /tone product |
| HPP | P6 | Natural Gas | 3.06 | GJ/GJ product |
| Waste Heat P6 | 2.06 | GJ/GJ product |
| EL-HPP | 1.00 | GJ/GJ product |

# Appendix C: model economic input data

*Table C1 CAPEX and OPEX of different waste recovery technologies*

| Specification | Amount | Reference |
| --- | --- | --- |
| **P14 (**heat recovery steam generator + steam turbine (HRSG+ST)**)** | | | |
| efficiency | 0.32 |  |
| Capacity (GT + ST) (TJ) | 6887 |  |
| Capacity (GT + ST) (kW) | 229,879 |  |
| total capital requirement (TCR) (€/kW) | 800 | (IEAGHG, 2020) |
| Cost ratio GT/ (HRSG+ST) | 1.16 | (Manzolini et al., 2015) |
| TCR, total (€) | 183,903,457 |  |
| TCR, P14 (k€) | 85,140 |  |
| AC, capital (k€/yr) | 9,961 |  |
| OPEX, fixed | 398 | (Kuramochi, Faaij, Ramírez, & Turkenburg, 2010) |
| AC, P14 | 10,360 |  |
| OPEX, var (k€/TJ) | 0.16 | (Manzolini et al., 2015) |
| Cost price generated electricity | 3.94 |  |
| **P16 (**absorption chiller (ABC)) | | | |
| efficiency | 0.72 | calculated (Oluleye, Jiang, Smith, & Jobson, 2017) |
| Capacity (TJ/yr) | 406.1 |  |
| Capacity (kW) | 13,554.4 |  |
| total capital requirement (TCR) (€/kW) | 500 | (U.S. Department of Energy, 2016) |
| Investment cost (k€) | 6,777 |  |
| AC, capital (k€/yr) | 793 |  |
| OPEX, fixed (k€/yr) | 29 | (U.S. Department of Energy, 2016) |
| AC, P14 | 822 |  |
| OPEX, var (k€/TJ) | 0.07 | (U.S. Department of Energy, 2016) |
| Cost price generated cooling | 2.1 |  |
| **P18 (**waste heat steam generator + Organic Rankine Cycle (WRSG+ORC)**)** | | | |
| type |  |  |
| efficiency | 0.14 | Nardin et al., 2018; Pili et al., 2020; Bause et al., 2015 |
| Capacity (TJ/yr) | 134.4 |  |
| Capacity (kW) | 4,486 |  |
| total capital requirement (TCR) (€/kW) | 1.82 | (Tenova, 2009); (Nardin et al., 2018) |
| Investment cost (k€) | 8,165 |  |
| AC, capital (k€/yr) | 955 |  |
| OPEX, fixed (k€/yr) | 120 | (Forni et al., 2014) |
| AC, P14 | 1,075 |  |
| OPEX, var (k€/TJ) | 0 |  |
| Cost price generated cooling | 8.0 |  |

*Table C2 Input prices and costs to the model*

|  |  |  |  |
| --- | --- | --- | --- |
| Resources | Value | unit | reference |
| Electricity at EN0 | 4.45 | €/GJ | (Noori, Korevaar, & Ramirez Ramirez, 2020) |
| Natural Gas at EN0 | 0.83 | €/GJ | (Noori et al., 2020) |
| Industrial Water | 0.14 | €/Nm3 | (Noori et al., 2020) |
| Pellet | 100.0 | €/tone | (Vogl, Åhman, & Nilsson, 2018) |
| DRI | 215.0 | €/tone | (Steelonthenet, 2020a) |
| Lime | 120.0 | €/tone | (Steelonthenet, 2020b) |
| Molasses | 100.0 | €/tone |  |
| Coke | 231.0 | €/tone | (Moya & Boulamanti, 2016) |
| scrap | 225.0 | €/tone | (LME, 2016) |
| Ferroalloys | 920.0 | €/tone | (Moya & Boulamanti, 2016) |
| Alumina | 279.5 | €/tone |  |
| Aluminum Fluoride | 1025 | €/tone |  |
| Cryolite | 900 | €/tone |  |
| Calcined coke | 200 | €/tone |  |
| Pitch | 200 | €/tone |  |
| slab | 410 | €/tone | (“Steel Price (Europe) | Historical Charts, Forecasts, & News,” n.d.) |
| Aluminum | 1440 | €/tone |  |
| CBI | 280 | €/tone | (Bhattacharyya, Biswas, & Rajib, 2019) |
| SMP variable cost | 66.5 | €/tone | (Vogl et al., 2018) |
| DRP variable cost | 27.5 | €/tone | (IEAGHG, 2013; Vogl et al., 2018) |
| ARP variable cost | 200 | €/tone | (Rosenberg, 2012) |

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