DOI: 10.3217/978-3-85125-842-4-13

144 Development of a Sustainable Steel Cluster in Iran through Industrial Symbiosis

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Abstract

Sustainable industrial development aims to increase living standards of people while providing solutions for environmentally and socially sound industrialization. Clustering is one of the main industrialization patterns in today's economies, and in order to define sustainable development of industrial clusters, the concept of Industrial Symbiosis (IS) has been defined for decades. Industrial clusters are complex systems in which the formation of IS is influenced by internal (e.g., technical characteristics of the plants and actors' previous collaborations) and external factors (e.g., energy prices and environmental limitations). Using a social-technical perspective, this paper will explore which symbiotic exchanges are more likely to occur in a cluster under various technical and institutional arrangements. The research was conducted in three main steps. First, the technical potential of IS was assessed by mapping the cluster technical structure, exploring the availability of waste flows for recovery, and finding matching demands for recovered flows. Second, based on a survey amongst the main actors of the cluster an institutional analysis was conducted. This analysis provided insight into current inter-industry collaborations, institutions guiding those collaborations, and drivers and barriers for extending them in the form of IS. Third, based on the collected data and information of the two first steps, the socio-technical structure of the cluster was modelled in Linny-R, a Mixed Integer Linear Programming software developed in Delft University of Technology. The conceptualization of the linear modelling is based on decomposing complicated industrial systems into a set of simple processes and products. The method was applied to a case of the Persian Gulf Mining and Metals Special Economic Zone (PGSEZ) in Iran. The results indicate that the presence of a coordination body in the cluster, does not guarantee collaboration between companies. The institutional analysis showed a discrepancy between stakeholders' preferences and governing legislations for future IS collaboration. Financial stimulation and infrastructure provision highly motivate stakeholders for IS, but institutional statements are unclear and ineffective in this regard. Bounding the economic parameters with technical and institutional conditions showed that symbiotic exchanges could result in higher cash flow and less electricity consumption of the whole cluster in case of an

increase in the grid electricity price or restrictions on its supply. Examining the flows between unit operations resulted in higher temperature waste heat and increased its quantity by 8%. Encouraging all actors to participate in the exchanges and governmental investment could boost the opportunities. As literature has rarely investigated industrial symbiosis cases in the Middle East, this study provides insight for future regional comparative studies. This conceptualization could be adjusted for any industrial cluster and its application is not limited to industrial symbiosis.

Keywords: industrial symbiosis, socio-technical perspective, cluster development, MILP

Acronyms and Symbols

Almahdi Aluminium Complex	AAC
Bandar Abbas City	BAC
Direct reduction plant	DRP
Electric arc furnace	EAF
Hormoz Power Plant	HPP
Hormozgan Steel Complex	HOS
Investment cost	IC
Iranian Mines and Mining Industries Development and Renovation Organization	IMIDRO
Kish South Kaveh Steel Company	SKS
Mixed integer linear programming	MILP
Operation cost	OC
Persian Gulf Mines and Metals Special Economic Zone	PGSEZ
Persian Gulf Saba Steel Company	SAB
PGSEZ management	PGM
Steelmaking plant	SMP

Introduction

Waste material or energy exchange among nearby industrial plants, which aim to gain a collective economic or environmental benefit, is defined as Industrial Symbiosis (IS) (Chertow, 2007). IS results in more sustainable production processes by recovering and utilizing one industry's waste flows in other industries. The geographical proximity of industries in clusters offers favorable conditions for IS implementation. A system-level approach is needed to study IS formation in an industrial cluster considering its technical, social, and economic conditions, since industrial clusters are complex socio-technical systems.

The first step in IS implementation on industrial clusters is to assess if a technical potential for IS exists. IS is based upon a material or energy exchange between a source and a sink in which the source is a waste flow. In a cluster, material and energy are exchanged between unit operations, plants, and companies. However, there is no consistency in the literature about the source and sink exploration. Most IS studies have examined plant outlet flows (Boons et al., 2016; Kastner et al., 2015; Notarnicola et al., 2016), while some recent IS studies have examined flows inside the plant for IS purposes. The latter approach overlaps with process integration methods. Moreover, in the sink exploration, IS possibilities in future cluster development are overlooked. Here is a need for a multi-level IS potential assessment method to explore sources and sinks for symbiotic at different levels.

The next consideration in IS assessment is to gain insight into actors' willingness to engage in IS collaboration. In the literature, previous collaborations (Spekkink and Boons, 2016), the existence of an anchoring actor (Sun et al., 2017), and a range of drivers are acknowledged to encourage actors in future IS collaborations (Ashton and Bain, 2012; Mortensen and Kørnøv, 2019; Yu et al., 2014). Besides, actors' behaviour in a socio-technical system is guided by shared visions, social norms, and legislations, called institutions collectively (Crawford and Ostrom, 1995). The linguistic expression of institutions is referred to as institutional statements. ADICO grammar of institutions, introduced by Crawford and Ostrom, is a powerful tool to investigate and interpret institutional statements, which has not been used in the IS field before. On the other hand, economic circumstances influence actors' investment decision on waste recovery exchange. This paper aims to understand how technical, social, institutional and economic conditions influence formation of IS in an emerging industrial cluster in the long term. Thus, all these aspects are incorporated in a mixed integer linear programming (MILP) model. For this purpose, Linny-R software, developed in Delft University of Technology (Bots, 2021), is used.

This paper proposes a systematic approach to identify possible IS collaborations in an industrial cluster considering its technical, social, and economic conditions. The methodology is elaborated in the case study of Persian Gulf Mines and Metals Special Economic Zone (PGSEZ). IS implementation in this industry could result in more sustainable industrialization. The case study implementation focuses on waste energy flows, although the methodology applies to both material and energy.

The paper is structured as follows: The methods section introduces the case study and four main steps toward IS assessment. Then, the results of different steps are presented and discussed. Finally, the conclusions and contribution of this work to IS studies are elaborated.

Methods

Figure 1 demonstrates the system-level approach implemented in this paper to investigate IS formation in an industrial cluster. First, we assessed internal and external technical, collaborative, institutional, and economic conditions that influence IS. Then, all these aspects were modelled together in Linny-R. Optimization procedure in Linny-R resulted in production level of different processes, and consequently their consumption and generation rates and actors' cash flow. Investment in waste recovery plants and other actors' decisions to buy recovered flow resulted in symbiotic exchanges.

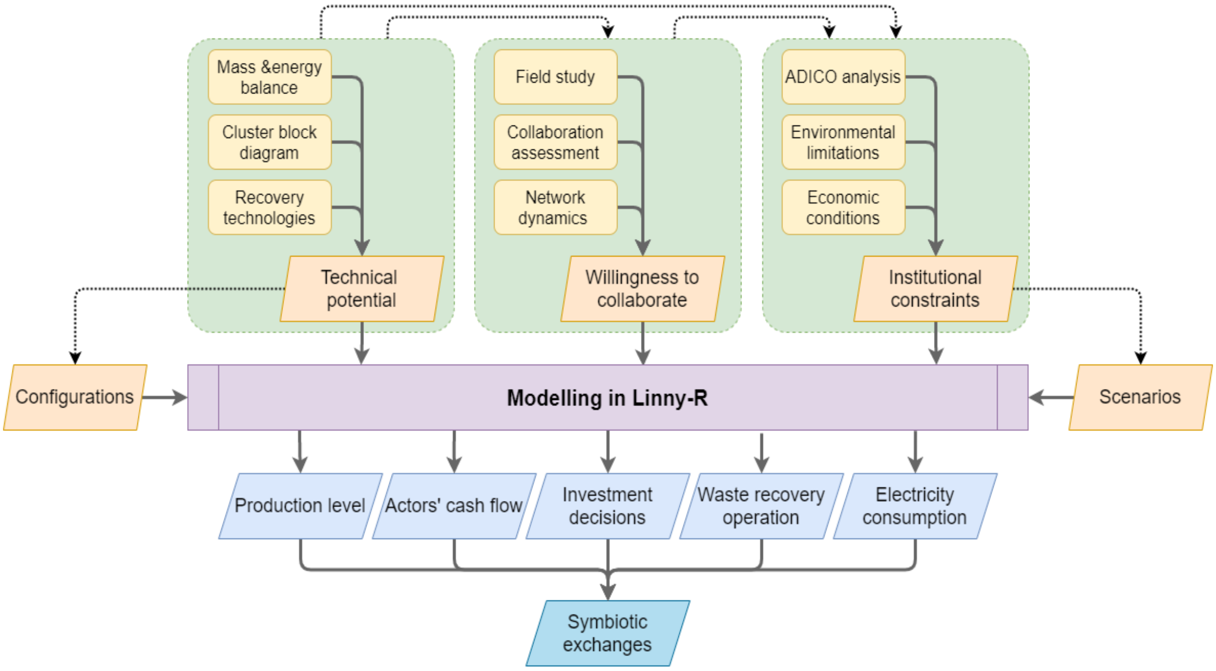

Figure 1 System-level approach implemented in this paper to study IS formation in a cluster

The case study

The method was implemented on the case study of PGSEZ in Iran. PGSEZ is located in the south of Iran, 14-kilometers from Bandar Abbas city (BAC), to utilize the advantage of proximity to the South Pars natural gas fields in developing energy-intensive metal processing industries. PGSEZ is an iron and steel-based industrial cluster located in the south of Iran. The iron and steel industry is one of the growing industries in emerging economies. World crude steel production has doubled during the last three decades, mainly by a steep increase in emerging economies. With 29 million tonnes yearly production, Iran stands in 10^{th} place in world crude steel production (WSA, 2021), with plans to reach 55 million tonnes capacity soon (SEAISI, 2017). However, steel production generates a wide range of pollutants (SEAISI, 2008; Villar et al., 2012). Six percent of global CO_2 emissions and eight percent of energyrelated emissions belong to iron and steel production. The cluster is managed by the state-owned corporation of Iranian Mines and Mining Industries Development and Renovation Organization (IMIDRO). PGSEZ management (here called PGM) is responsible for coordinating activities and providing shared infrastructure for industries. PGSEZ has several development plans either inside existing companies or establishing new industries. However, industrial development in Iran suffers from water scarcity (Madani, 2014; Madani et al., 2016), high CO_2 emissions (Global Carbon Project, 2016), and sanctions. Active companies in PGSEZ are three steel production (SKS, HOS, and SAB), an aluminum production (AAC), and one gas turbine power plant (HPP). An under-construction pelletizing plant was not considered in this study.

Table 1 Companies and plant located in PGSEZ with their production capacities

Company	Plant	Type	Capacity
Kish South Kaveh Steel Company (SKS) (sksco.ir/)	P1	Midrex direct reduction	1,850,000 t/year
	P2	EAF steelmaking	1,200,000 t/year
Hormozgan Steel Complex (HOS) (hosco.ir/)	P3	Midrex direct reduction	1,650,000 t/year
	P4	EAF steelmaking	1,500,000 t/year
	P5	Cold Briquetting	75,000 t/year
Hormoz Power Plant (HPP) (pgsez.ir/)	P6	Gas turbine power plant	160 MW
Persian Gulf Saba Steel Company (SAB) (sabasteel.co)	P7	Midrex direct reduction	1,000,000 t/year
Almahdi Aluminum Complex (AAC) (almahdi.ir/)	P8	Anode Baking	93,000 t/year
	P9	Hall-Héroult Aluminum Refining	172,000 t/year

Technical potential assessment

Industrial networks can be presented as a collection of sources and sinks (Kastner et al., 2015). In IS context, sources are waste flows, and sinks are processes or plants which consume these sources. A previous study (Noori et al., 2021) has proposed a method to uncover technically possible symbiotic exchanges which have not become functional yet. The methodology was based on identifying sources and sinks and matching between them considering recovery technologies. For this purpose, first, all incoming and outgoing material and energy flows of every plant were mapped. Flow rates were gathered during site visits or obtained from literature or calculated based on mass and energy balances where field data was not available.

As stated in the introduction, the system boundaries for source and sink exploration have not been defined in the literature explicitly. We explored sources and sinks at different levels to investigate the effect of boundary settings on perceived technical potential. For source exploration, we first looked up plant outflows. Then, these flows were traced back inside plant boundaries for any processing before disposals, such as cooling and dilution. In sink exploration, first, we searched for energy demand inside the cluster. Then, utilization possibilities in the nearby urban area or future cluster development were explored. In the end, the technology ranking framework developed by Oluleye et al. (2017) was implemented to select the most suitable heat recovery options based on source temperature and sink type (heating, cooling, or electricity).

Social readiness for IS

To get insight into cluster social readiness for IS formation; a previous study (Noori et al., 2020) was conducted on two grounds: A field study to understand the internal social structure of the cluster and institutional analysis to investigate national or regional rules and regulations governing IS implementation in Iran.

Collaboration assessment

For the field study, a three-part questionnaire was distributed among managers and deputies of the companies. In the first part, called the collaborations matrix, the respondents were asked to indicate if they have had previous collaborations that could lead to future symbiotic exchanges. Such activities are called pre-emergence collaborations (Spekkink and Boons, 2016). Asked pre-emergence collaborations in the questionnaire were technical advice and consultation, supervision and project management, product trade, by-product trade, utility supply, and joint investment. In the second part, the structure of successful collaborations was studied in terms of involved stakeholders and their roles. In the last part, IS drivers from the literature were ranked by respondents to uncover which drivers are the most dominant in this cluster.

ADICO institutional analysis

ADICO grammar of institutions is a systematic approach to study institutional statements (Basurto et al., 2010). Five ADICO components are attribute (A), deontic (D), aim (I), condition (C), and or else (O). To implement ADICO in IS field, we adapted it to IS dynamics framework introduced by Boons et al. (2016) (Table 2). Attributes were classified to the industry, cluster management, and government and governmental organizations. Aims were also categorized into nine IS-related topics. For this purpose, as the first step of institutional analysis, regulations governing development, environmental protection, and energy efficiency in the industrial sector were chosen among national documents. The list of selected law books and procedures was checked with experts in the cluster to ensure all currently effective regulations are considered. Then, all clauses, paragraphs, and notes were separated and copied to an excel sheet, complicated parts were broken into simple ones. The investigation scope narrowed down to IS-related statements (e.g., cluster development, waste management, and energy recovery). Subsequently, five ADICO components were distinguished for each statement. Not every institutional statement includes all components. Rules incorporate all five components, norms do not declare penalties or sanctions, and shared strategies are composed of an attribute, aim, and condition only.

Table 2 ADICO grammar linked to IS dynamics (Noori et al., 2020)

Attribute	Deontic	Topic	Condition	Or else
Government/ Governmental Organisation Cluster Management Industries	Obligation Permission Prohibition	Pricing Eco-efficiency improvement Infrastructure provision Market brokerage Knowledge development and awareness Economic stimulation Industrial and Cluster development Regulatory and legislation Environmental monitoring and assessment	When Where If Unless	Penalties Sanctions

Economic conditions

In general, waste heat must be recovered before utilization in other plants. Starting a new waste recovery plant (WR) has investment and operation expenses and influences the actor's cash flow. Therefore, all costs associated with the operation of existing plants and future WRs were estimated. It was assumed that existing plants have been paid off already. Therefore, investment cost was assigned to WRs only. Capital cost for different waste recovery technologies was obtained from literature and adjusted by Middle East location factors. The equivalent annual cost was calculated assuming an interest rate of 10% and a lifetime of 20 years (Equation 1 and 2). Annualized cost was calculated based on Equation 3 and was deducted from actor's cash flow in case WR came into operation. Domestic and industrial electricity and natural gas prices were obtained from a previous study (Noori, 2020), raw material and product prices were collected from publicly available price lists, and operation costs obtained from similar plants, adjusted by location factors (Rubin et al., 2021).

$$CRF = \frac{R}{1 - (1 + R)^{-n}} \quad \text{(Eq. 1)}$$

$$EAC = Capital\ cost \times LF_{inv} \times CRF \quad \text{(Eq. 2)}$$

$$AC = EAC + (O\&M_{fixed} \times LF_{labour}) \quad \text{(Eq. 3)}$$

Where:

AC: annualized cost

EAC: equivalent annual cost

CRF: capital recovery factor

R: interest rate

n: lifetime

$O\&M_{fixed}$: fixed operation and maintenance cost

$O\&M_{var}$: variable operation and maintenance cost

LF_{inv}: Investment cost location factor (material cost factor x contingency factor)

LF_{labour}: labour cost location factor (labour productivity factor x labour cost factor)

Cluster modelling in Linny-R

Linny-R is a diagram-based MILP modelling tool for techno-economic analysis and optimization of industrial systems. The building blocks of a Linny-R model are products and processes. Linny-R also accepts non-physical processes and flows, which provides the opportunity to incorporate non-physical activities such as buying, selling, contracting, or willingness in the model. Constraints and prices can be assigned to non-physical processes in the same way as physical ones.

To study IS formation; the current structure of the cluster was built in Linny-R first. Each production plant modelled as a process and its incoming and outgoing flows as products. Production capacities and flow rates were obtained from the integrated cluster block diagram, and process expenditures and revenues were collected during economic inventory. Then, designated waste recovery units and possible exchanges were added to the model to investigate which collaborations could shape in the cluster under given technical, social, and economic conditions. Modelling period was selected to be 20 years with time steps of one year. The main Linny-R functionalities regarding waste recovery and exchange are elaborated in this section.

Conceptualizing waste recovery and exchange decision

Figure 2 shows how symbiotic exchanges were conceptualized in this study. The conceptualization has three pillars: decomposing IS to a set of physical and non-physical activities, applying system constraints to processes and products, and giving actors the opportunities to select among different routes in each step. In this conceptualization, actors decide for waste recovery and exchange based on their economic benefit and willingness to collaborate. Waste flow W, which is generated by actor k, could be sent to waste disposal (WD) or recovered in waste recovery (WR) in the form of R’ $_{\text{recovered}}$. In general, R’ $_{\text{recovered}}$ could be used internally by actor *k* or sold to the other actors. On the other hand, actor *h* could buy resource R' from the market or actor *k*. IS shapes when actor *k* chooses WR over WD, and actor *h* selects R’ $_{\text{recovered}}$ over R’ $_{\text{market}}$. This conceptualization represents self-organized IS in which two actors collaborate without intervention or facilitation by the cluster management or governmental organizations.

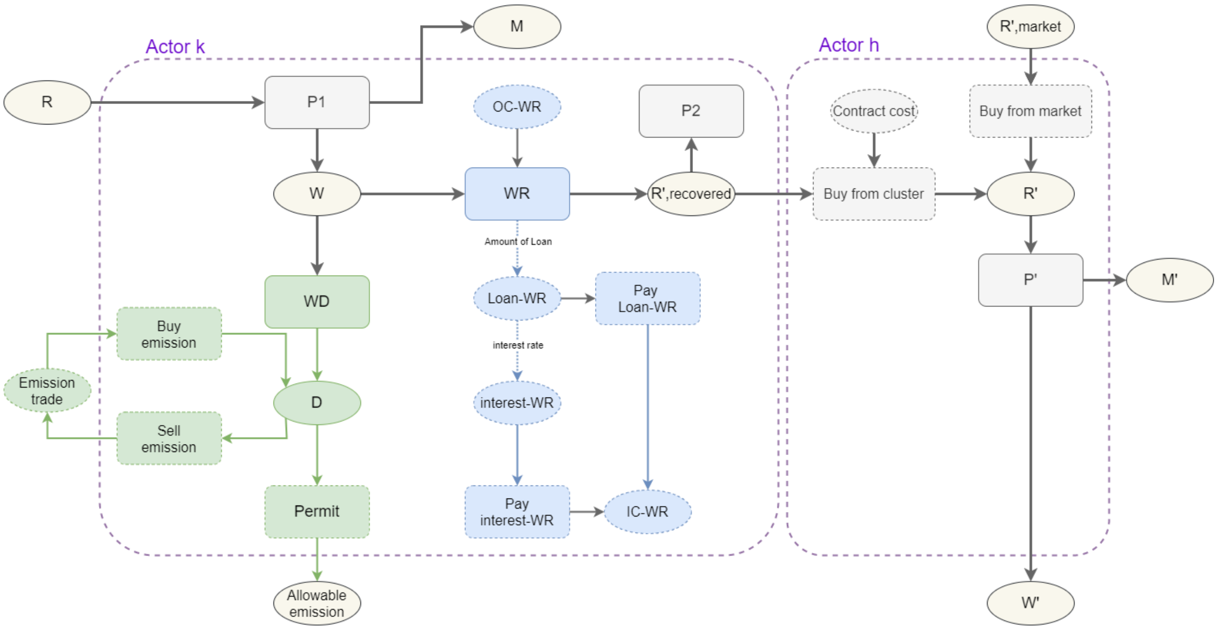

Figure 2 Formation of IS among two actors

All processes and products in Figure 2 are subjected to socio-technical costs and constraints. WD is limited by price-based or quantity-based emission control policies. The figure shows how such limitations are detailed in Linn-R by either assigning an upper bound on allowable disposal or negative price on emission trade. On the other hand, WR exerts new investment cost (IC) and operation cost (OC) on actor *k*. As illustrated in this figure, OC and IC could be deducted from the actor's cash flow using data type products (dotted ones). However, symbiotic exchange will not shape if the two actors are not interested in collaboration with each other. We reflected actors' willingness to collaborate in the upper bound of the "Buy from cluster" process.

Furthermore, exchange costs (e.g., contracting and transportation) are assigned to this process.

Configurations and scenarios

In this paper, we built two configurations of the cluster as listed in Table 3. WR0 represents the cluster without any waste recovery and exchange. In WR+, waste recovery plant P14 was added to the model to recover the high-grade waste heat generated in the power plant as electricity. The generated electricity can be consumed by other companies inside the cluster or sent to Bandar Abbas (BAC) to be used in conventional air conditioners for cooling purposes. Household electricity demand for cooling was obtained from nationally available data for Hormozgan province and considered to increase yearly proportional to population growth. As elaborated in Table 4, three energy price scenarios were examined on each configuration to study cluster operation and IS formation under varying external factors.

Table 3 Waste recovery and exchange possibilities in configurations WR0 and WR+

Configuration	Waste recovery	Possible exchanges
WR0	No waste recovery exists	No symbiotic exchange
WR+	Electricity recovery from WH,P6 (P14)	HPP electricity exchange with SKS, HOS, SAB, AAC, and BAC

Table 4 Energy price scenarios considered in this study

Scenario	Explanation
EN0 (Fixed)	No change in electricity and natural gas prices during the next 20 years
EN+ (Moderate rise)	10% annual rise in electricity and natural gas prices increase over the next 20 years
EN* (Drastic rise)	Electricity and natural gas prices doubled and then increase with the rate of 10% over the next 20 years

Results and Discussion

Integrated cluster block diagram

Integrating block diagrams of all production and utility plants in the form of cluster block diagrams provided knowledge about the material and energy performance of the whole cluster. Yearly, 4.32 million tonnes main product was produced from 8.89 million tonnes input raw material. 4.57 million Tonnes of gaseous or solid by-products were also generated, which means the material productivity of the whole cluster was around 49%. From 1,448 MW energy input to PGSEZ in the form of electricity, natural gas, and coke, around 41% (592 MW) was emitted as high, medium, and low-grade waste heat streams. 160 MW electricity was generated and consumed inside the cluster. 21.89 million m^3 seawater was taken, and 14.91 million m^3 brine was disposed to the gulf yearly, plus 3.68 million m^3 of industrial wastewater.

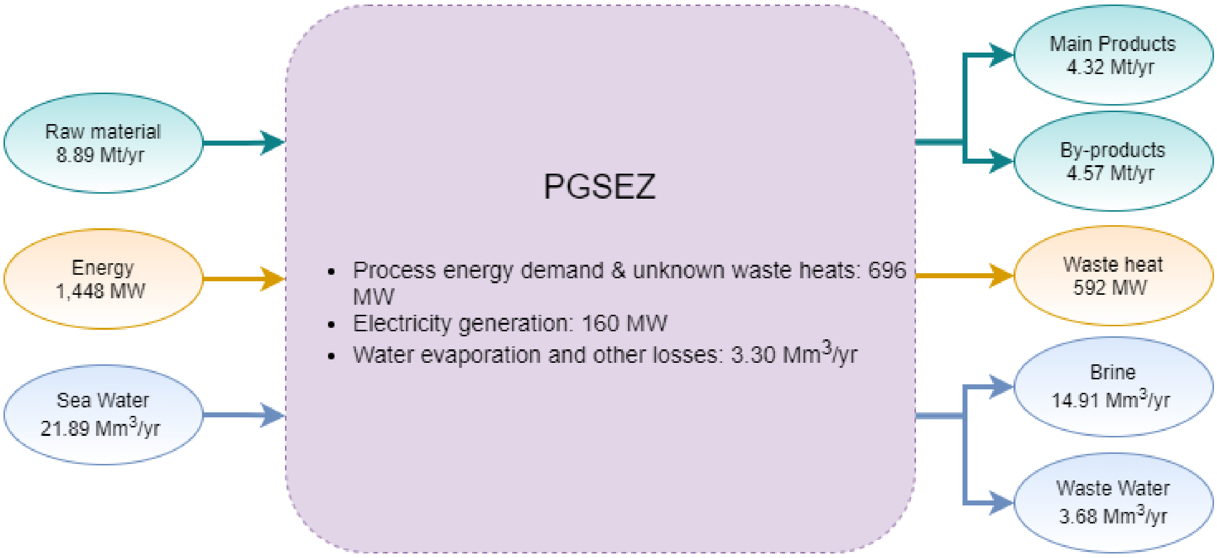

Figure 3 Cluster block diagram incorporating material, energy, and water flows

Multi-level assessment of energy exchange potential

As stated in the previous section, 592 MW waste heat was spotted by studying plant output flows. In plant-level source exploration, process flow diagrams of steelmaking (SMP) and direct reduction (DRP) plants were studied in more detail. SMP investigation revealed that electric arc furnace (EAF) flue gas, which carries theoretically 15 to 35 percent of EAF energy input (Barati, 2010; Kirschen et al., 2011), is mixed with other gases and cooled down before exhaust at 90 °C. Utilizing energy content of this flow for IS before mixing and cooling replaces 40 MW low-grade heat with 85 MW high-grade heat. In DRP, combustion flue gas is diluted with fresh air before disposal because of environmental limitations. High-grade waste heat will be available for IS purposes if the flue gas is utilized before dilution. In multi-level sink exploration, intra-cluster and outside-cluster utilization were examined, and suitable waste recovery technology was selected according to Oluleye et al. (2017). Intra-cluster demand was considered electricity, while outside cluster utilization was chosen based on first ranked technology. The results are summarized in Table 5. It shows that source exploration at the intra-plant level reveals higher qualities and quantities of available waste heat. Besides, waste heat can be recovered in the form of cooling or heating through more efficient technologies if sink exploration is not limited to intra-cluster demands.

Table 5 Multi-level comparison of IS potential in PGSEZ (Noori et al., 2021)

	Available waste heat (MW)	**Temperature (°C)**	**Energy exchange potential (MW)**			
			Intra- Cluster		1st ranked technology	
			Amount	Form	Amount	Form
Plant input-output	40	90	4 (1)	electricity	28 (2)	cooling
	75	150	13 (3)	electricity	90 (4)	cooling
	130	300	35 (5)	electricity	104 (7)	heating
	330	500	106 (6)	electricity	264 (7)	heating
Intra-plant level	75	150	13 (3)	electricity	90 (4)	cooling
	130	450	42 (6)	electricity	104 (7)	heating
	330	500	106 (6)	electricity	264 (7)	heating
	85	1100	27 (6)	electricity	68 (7)	heating

(1) ORC efficiency for low-temperature input heat was assumed 10% (Oluleye et al., 2016)
(2) Single-stage absorption chiller COP was assumed 0.7 (Reddy, 2013)
(3) ORC efficiency was assumed 17% (Oluleye et al., 2016)
(4) Double stage absorption chiller COP was assumed 1.2 (Reddy, 2013)
(5) ORC efficiency was assumed 27% (Oluleye et al., 2016)
(6) The efficiency of the HRSG plus steam turbine is assumed 32% (Ahmed et al., 2018).
(7) The average efficiency of heat recovery heat exchangers was considered 80% (Jouhara et al., 2018)

Previous collaborations and the role of cluster management

As illustrated in Figure 4, most pre-emergence collaborations were shaped among three steel production companies or cluster management. The next part of the questionnaire revealed that the cluster management or other governmental organizations were involved in around 75% of successful collaborations in the last five years. Nevertheless, they have provided the required infrastructures for less than 30% of collaborations. In addition, involved industries have initiated activities themselves. Among different IS drivers, the respondents admitted infrastructure readiness, governmental financial stimulations, and resource scarcity as the most encouraging motives to engage in new IS collaborations. On the other hand, workshops and seminars, lowering Greenhouse Gas Emissions, and rising waste disposal costs were less prominent drivers for the respondents.

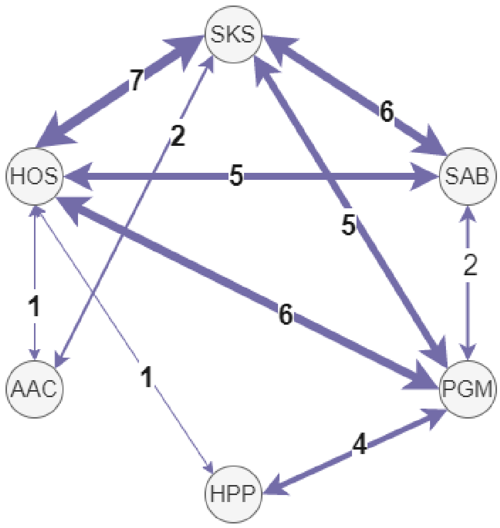

Figure 4 Number of pre-emergence collaborations among different actors during the last five years

Institutional lens upon IS

Figure 5 outlines the results of ADICO analysis. Among 183 institutional statements, only 19 were identified as rules, with an explicit penalty or sanction in case of violation. In addition, the role of cluster management was not elaborated in the legislation, as we found only five statements with cluster management as an attribute. In topic, most statements proposed eco-efficiency improvement, environmental monitoring and assessment, and industrial or cluster development. It could be said that legislation in Iran does not support either facilitated IS or eco-clustering considering only a few statements regarding infrastructure provision, knowledge development, and market brokerage. Self-organization and governmental planning are the most supported dynamics by legislation. This finding was in line with the field study outcomes which showed the despite existence of cluster management team, the most successful previous collaborations have been initiated and facilitated by the industries themselves.

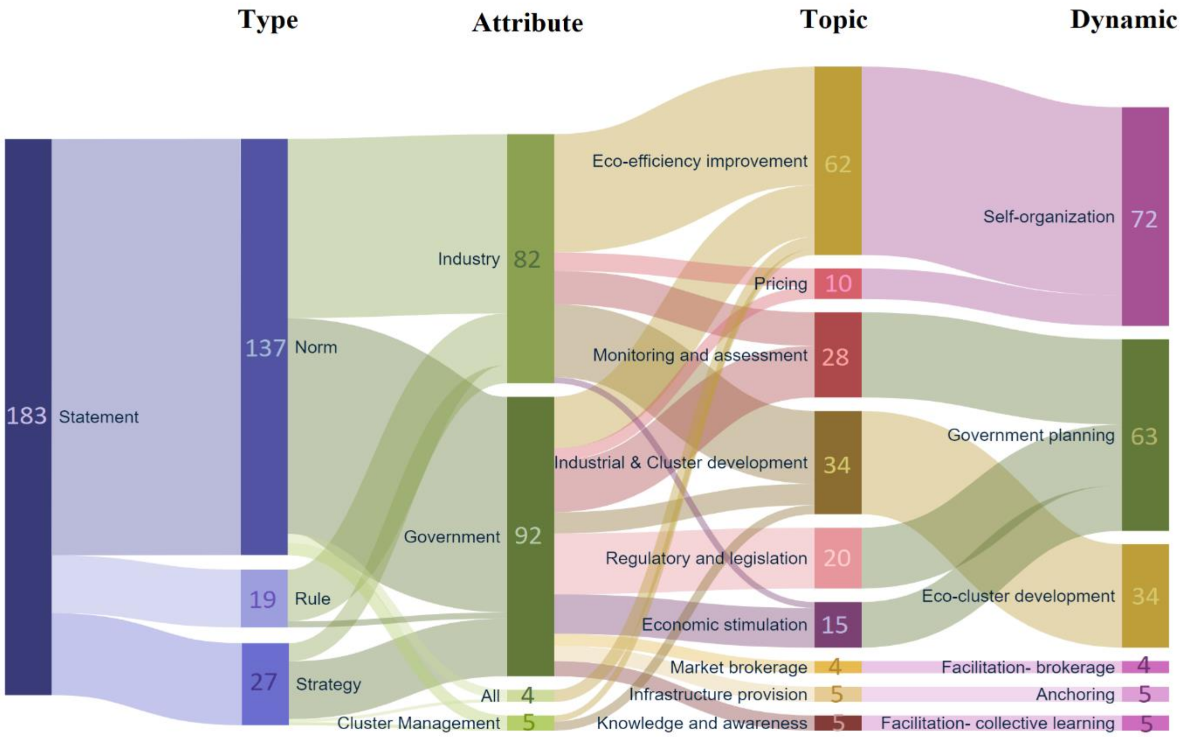

Figure 5 Composition of invetigated institutional statements in terms of type, attribute, aim, and supported IS dynamic (Noori et al., 2020)

Production levels and cash flows

Before investigating the operation of waste recovery units, the production level of nine industrial plants was studied under three energy price scenarios. Under the EN0 scenario, the production level of all plants remained fixed over 20 years. However, by a 10% yearly rise in electricity and natural gas prices, the plants shut down after few years. The aluminum plant, which is the most energy-intensive one, stopped after eight years. Then, plants in HOS, SKS, and SAB stopped operation one after each other (Figure 6). The same pattern was observed in EN* scenario, but with a more severe drop in production levels. Nevertheless, power plant operation was not influenced by the rise in energy price. Comparing cluster operation in WR0 and WR+ configurations revealed that the existence of waste recovery and exchange aided plants' production up to higher energy prices. As energy cost is one of the main expenditures of steel and aluminum industries, all actors' cash flow dropped due to energy price increment. Again, the drop was more drastic in EN* scenario compared to EN+. Only the power plant's cash flow increased, as this plant earned more from electricity generation.

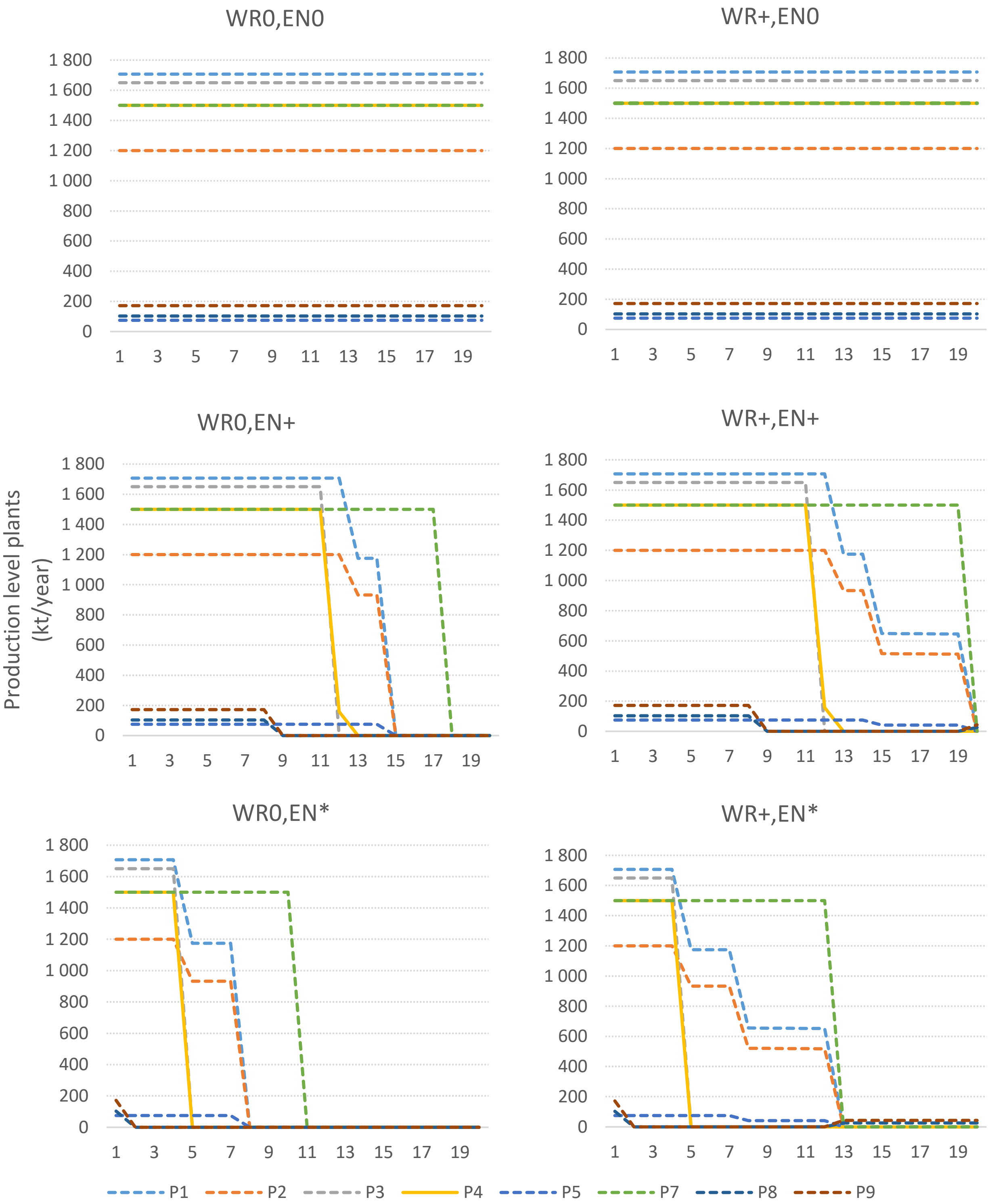

Figure 6 Production level of industrial plants under different scenarios and configurations

Waste recovery and symbiotic exchanges

P14 came into operation in all three scenarios. Recovered electricity in P14 found different destinations under different scenarios. In all scenarios, recovered electricity was cheaper than urban electricity price. Therefore, BAC received all its electricity demand from recovered electricity in the cluster. By increase in energy prices in the EN+ scenario, four aluminium and steel industries inside the cluster also consumed part of recovered electricity. However, the capacity of P14 exceeded cluster internal demand, and excess electricity was sent to the grid. However, electricity supply to the grid is not categorized as IS by definition. Details of exchanged electricity among actors are illustrated in Figure 6. In EN* scenario, all recovered electricity was exchanged with the other actors, and there was no electricity supply to the grid. Recovered electricity consumption by AAC increased significantly in this scenario. As explained in the previous section, AAC stopped production after one year in this scenario. But, the company was able to come into operation again in the last eight years by receiving recovered electricity from HPP. It was not possible to interpret symbiotic exchanges in this figure without understanding the production plant's behaviour under different scenarios. Hence, IS cannot be understood separately from the whole cluster operation.

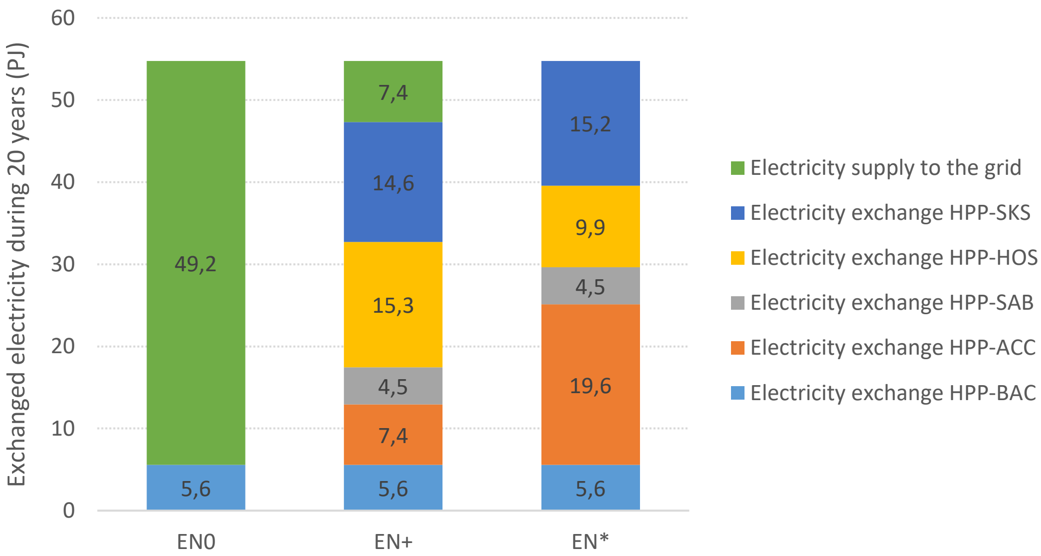

Figure 7 Amount of exchanged electricity between actors over 20 years

Cluster performance improvement

In this study, cluster cash flow and grid electricity consumption were studied as cluster economic and energy performance indicators. As shown in Table 6, both measures improved because of introducing waste recovery and exchange options to the cluster. As explained previously, cluster cash flow and electricity consumption dropped by increasing energy prices. However, cash flow was higher in WR+ compared to WR0 under all scenarios despite all expenses required for IS formation (investment, operation, and contract costs). Negative net grid electricity intake values in Table 6 express supply from the grid. Around 54.8 PJ less grid electricity was consumed in the presence of waste recovery units. It showed that techno-economically feasible IS connections are not in line with actors' willingness to collaborate necessarily. HPP can improve cluster energy performance significantly if engaged in IS collaborations, although the company has not collaborated with the other actors in PGSEZ before.

Table 6 Changes in cluster economic and energy performance in 20 years under different configurations and scenarios

Configuration	WR0			WR+		
Scenario	**EN0**	**EN+**	**EN***	**EN0**	**EN+**	**EN***
Cluster cash flow (M€)	5,062.6	2,226.6	1,026.6	5,092.7	2,606.1	1,441.6
Net grid electricity intake (PJ)	-311.9	-122.4	15.3	-257.2	-80.0	40.4

Conclusions

In this study, frameworks from waste heat utilization, the emergence of collaborations, institutional analysis, and IS dynamics are integrated and utilized to provide a holistic insight into the complex structure of industrial clusters. Then, this complex structure was modelled in Linny-R to investigate the cluster performance, specifically IS formation, under different circumstances.

The multi-level technical potential assessment showed that higher quality or quantity of waste heat might be available for IS purposes if waste flows are examined inside plant boundaries. Furthermore, recovered waste heat can find new destinations if sink exploration covers the nearby urban area or future cluster development possibilities. Although this paper focused on energy exchange assessment, the methodology applies to material networks as well.

In collaboration assessment, we investigated pre-emergence collaborations and their structure to get insight into actors' willingness to start IS. It revealed that, despite presence of a centralized management body in the cluster, pre-emergence collaborations were often self-organized. It was also inquired which IS drivers are more influential in the cluster, which led to infrastructure readiness, financial aid, and resource scarcity.

ADICO grammatical syntax was implemented to investigate legislation about IS implementation in Iran. Our analysis showed that although regulations encourage energy efficiency improvement and environmental monitoring, explicit penalties and sanctions in case of violation are not specified. Moreover, the responsibilities and authorities of cluster management were not elaborated in national-level legislation.

This modelling work shed light on the fact that ISO cannot be investigated as a standalone phenomenon. Changes in cluster internal or external conditions affect the operation of industrial plants and waste recovery plants simultaneously, so the whole cluster must be studied as a system. This method also reveals contradictions between techno-economically feasible IS collaborations and involved actors' willingness to collaborate. This outcome provides more realistic insights into socio-technically favourable collaborations and actors' investment decisions.

We investigate IS collaborations at the system level within the complex structure of the cluster. Under assumed conditions, symbiotic exchanges covered all required investment, operation, and contract costs and brought economic benefit for the cluster in the long term. It should be noticed that these conclusions are valid for conceptual design and system-level analysis. The establishment of suggested collaborations calls for more specific technical and economic considerations. However, IS is not the only sustainable industrial development strategy. At the system level, IS might create industrial decarbonisation synergies in combination with other options such as carbon capture and storage, which calls for further research.

Appendix A: Model input data

Table A1 Material and energy consumption and generation rates in different processes in PGSEZ (Noori et al., 2021)

Actor	Product	Process	flow rate	Unit
SKS	Pellet	P1	1.45	tonne/ tonne product
SKS	DRI,SKS	P1	1.00	tonne/ tonne product
SKS	Sludge,D	P1	0.05	tonne/ tonne product
SKS	Dust,D-SKS	P1	0.06	tonne/ tonne product
SKS	EL,i-SKS	P1	0.47	GJ/tonne product
SKS	NG-FS	P1	0.20	tonne/ tonne product
SKS	NG	P1	1.58	GJ/tonne product
SKS	WH,P1	P1	0.71	GJ/tonne product
SKS	IW	P1	1.00	Nm^3/tonne product
SKS	WW	P1	0.40	Nm^3/tonne product
HOS	Pellet	P3	1.45	tonne/ tonne product

Actor	Product	Process	flow rate	Unit
HOS	DRI,HOS	P3	1.00	tonne/ tonne product
HOS	Sludge,D	P3	0.06	tonne/ tonne product
HOS	Dust,D-HOS	P3	0.03	tonne/ tonne product
HOS	EL,i-HOS	P3	0.42	GJ/tonne product
HOS	NG,FS	P3	0.20	tonne/ tonne product
HOS	NG	P3	1.58	GJ/tonne product
HOS	WH,P3	P3	0.75	GJ/tonne product
HOS	IW	P3	1.02	Nm^3/tonne product
HOS	WW	P3	0.30	Nm^3/tonne product
SAB	Pellet	P7	1.37	tonne/ tonne product
SAB	HBI	P7	1.00	tonne/ tonne product
SAB	Sludge,D	P7	0.02	tonne/ tonne product
SAB	Dust,D	P7	0.02	tonne/ tonne product
SAB	EL,i-SAB	P7	0.50	GJ/tonne product
SAB	NG,FS	P7	0.19	tonne/ tonne product
SAB	NG	P7	1.49	GJ/tonne product
SAB	WH,P7	P7	0.72	GJ/tonne product
SAB	IW	P7	1.72	Nm^3/tonne product
SAB	WW	P7	0.69	Nm^3/tonne product
SKS	Scrap	P2	0.02	tonne/ tonne product
SKS	DRI,SKS	P2	1.26	tonne/ tonne product
SKS	Lime	P2	0.07	tonne/ tonne product
SKS	Ferroalloys	P2	0.03	tonne/ tonne product
SKS	Coke	P2	0.49	GJ/tonne product
SKS	Billet	P2	1.00	tonne/ tonne product
SKS	Slag	P2	0.26	tonne/ tonne product
SKS	Dust,S	P2	0.01	tonne/ tonne product
SKS	Sludge,S	P2	0.05	tonne/ tonne product

Actor	Product	Process	flow rate	Unit
SKS	Loss,CCM	P2	0.02	tonne/ tonne product
SKS	EL,i-SKS	P2	2.70	GJ/tonne product
SKS	NG	P2	0.18	GJ /tonne product
SKS	WH,P2	P2	0.47	GJ/tonne product
SKS	IW	P2	1.12	Nm^3/tonne product
SKS	WW	P2	0.53	Nm^3/tonne product
HOS	Scrap	P4	0.03	tonne/ tonne product
HOS	DRI,HOS	P4	1.23	tonne/ tonne product
HOS	Lime	P4	0.06	tonne/ tonne product
HOS	Ferroalloys	P4	0.05	tonne/ tonne product
HOS	Coke	P4	0.20	GJ /tonne product
HOS	Slab	P4	1.00	tonne/ tonne product
HOS	Slag	P4	0.26	tonne/ tonne product
HOS	Dust,S	P4	0.01	tonne/ tonne product
HOS	Sludge,S	P4	0.08	tonne/ tonne product
HOS	Loss,CCM	P4	0.02	tonne/ tonne product
HOS	EL,i-HOS	P4	2.76	GJ /tonne product
HOS	NG	P4	0.11	GJ /tonne product
HOS	WH,P4	P4	0.34	GJ /tonne product
HOS	IW	P4	0.93	Nm^3/tonne product
HOS	WW	P4	0.53	Nm^3/tonne product
AAC	Calcined Coke (CPC)	P8	0.60	tonne/ tonne product
AAC	Pitch (CTC)	P8	0.15	tonne/ tonne product
AAC	Spent Anode	P8	0.25	tonne/ tonne product
AAC	Anode	P8	1.00	tonne/ tonne product
AAC	NG	P8	2.45	GJ /tonne product
AAC	EL,i-AAC	P8	0.50	GJ /tonne product
AAC	WH,P8	P8	0.56	GJ /tonne product

Actor	Product	Process	flow rate	Unit
AAC	Alumina	P9	1.96	tonne/ tonne product
AAC	Cryolite	P9	0.03	tonne/ tonne product
AAC	Aluminum fluoride	P9	0.04	tonne/ tonne product
AAC	Anode	P9	0.45	tonne/ tonne product
AAC	Aluminum ingot	P9	1.00	tonne/ tonne product
AAC	SPL	P9	0.02	tonne/ tonne product
AAC	EL,i-AAC	P9	56.88	GJ /tonne product
AAC	WH,P9	P9	11.38	GJ /tonne product
HOS	Lime9	P5	0.02	tonne/ tonne product
HOS	Molasses	P5	0.04	tonne/ tonne product
HOS	CBI	P5	1.00	tonne/ tonne product
HOS	EL,i-HOS	P5	0.06	GJ /tonne product
HPP	NG	P6	3.06	GJ /kWh product
HPP	WH,P6	P6	2.06	GJ /kWh product
HPP	EL-HPP	P6	1.00	GJ /kWh product

Table A2 Input prices and costs

Resources	Value	unit	reference
Electricity at EN0	4.45	€/ Gj	(Noori et al., 2020)
Natural Gas at EN0	0.83	€/ Gj	(Noori et al., 2020)
Industrial Water	0.14	€/Nm^3	(Noori et al., 2020)
Pellet	100.0	€/tonne	(Vogl et al., 2018)
DRI	215.0	€/tonne	(Steelonthenet, 2020a)
Lime	120.0	€/tonne	(Steelonthenet, 2020b)
Molasses	100.0	€/tonne	
Coke	231.0	€/tonne	(Moya and Boulamanti, 2016)
scrap	225.0	€/tonne	(LME, 2016)
Ferroalloys	920.0	€/tonne	(Moya and Boulamanti, 2016)

Resources	Value	unit	reference
Alumina	279.5	€/tonne	
Aluminum Fluoride	1025	€/tonne	
Cryolite	900	€/tonne	
Calcined coke	200	€/tonne	
Pitch	200	€/tonne	
slab	410	€/tonne	(“Steel Price (Europe) | Historical Charts, Forecasts, & News,” n.d.)
Aluminum	1440	€/tonne	
CBI	280	€/tonne	(Bhattacharyya et al., 2019)
SMP variable cost	66.5	€/tonne	(Vogl et al., 2018)
DRP variable cost	27.5	€/tonne	(IEAGHG, 2013; Vogl et al., 2018)
ARP variable cost	200	€/tonne	(Rosenberg, 2012)

Table A3 Techno-economic characteristics of added waste recovery unit in configuration (b)

Actor	WR Process	Type	Output	Efficiency (%)	Capacity (GJ)	Investment (k€)	Operation Cost (k€/GJ)
HPP	P14	STP	EL	32	2,730	105,000	0.7

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