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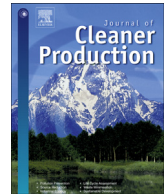
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# Assessing industrial symbiosis potential in Emerging Industrial Clusters: The case of Persian Gulf Mining and metal industries special economic zone

Shiva Noori<sup>\*</sup>, Gijsbert Korevaar, Andrea Ramirez Ramirez

Department of Engineering Systems & Services, Faculty of Technology, Policy and Management, Delft University of Technology, Jaffalaan 5, 2628, BX Delft, the Netherlands

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## ABSTRACT

Industrial Symbiosis (IS) is a means for sustainable cluster development. The first consideration for implementing IS in a cluster is to identify technical opportunities for exchanging waste material and/or energy. However, the definition and methods for assessing the technical potential of IS are not elaborated in the literature. This research proposes a method to evaluate IS potential that considers different system boundaries. The method allows for explicitly reflecting current and expected developments at plant and cluster level. The suggested method was applied to the Persian Gulf Mining and Metals Special Economic Zone (PGSEZ) in Iran. The case study shows that expanding the system boundaries to include the waste flows inside steelmaking and direct reduction plants could result in an 8% increase in available waste heat. Heat recovery possibilities outside the cluster boundaries offered 118 MW cooling plus 368 MW heating potential compared to 158 MW demand for electricity in the cluster. Furthermore, less than 20% of generated by-products could currently be reused in the cluster, while theoretically all by-products could be utilized today in other industries such as cement and ceramic. These findings support the use of IS as a way to open new perspectives for EIC development policies.

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## 1. Introduction

Clustering is one of the main industrialization patterns in today's economies (Porter, 1998). Industrial clusters are complex socio-technical systems composed of several actors. Actors benefit from clustering in the form of supply chain, utility and service sharing, and by-product and waste exchange (UNIDO, 2017). The concept of Industrial Symbiosis (IS) takes into account the complexity of the industry-society-environment system in industrial clusters. IS has been defined as a collaborative relationship between nearby industrial plants to exchange waste material or energy and achieve economic and environmental benefits that cannot be gained individually (Chertow, 2007). Emerging Industrial Clusters (EICs) are clusters in their first stages of evolution with unrealized possibilities for rapid growth (Teräs, 2011). EICs are expected to play an influential role in the industrialization of emerging economies. Although IS is acknowledged as a way toward

sustainable industrial development (Van Berkel, 2010), the first consideration to implement IS in EICs is to establish if any potential for waste material and energy exchange does indeed exist (Kastner et al., 2015).

Industrial clusters can be examined at different levels: a cluster can be composed of different companies where each company can include one or more industrial plants, working mostly in the same industrial supply chain (Kastner et al., 2015). An industrial plant, in turn, is a set of unit operations to produce the desired product from raw materials (Douglas, 1988). Material and energy exchanges take place between unit operations, plants, and companies. Nevertheless, it is not clear in the literature which levels are considered when assessing potentials of IS. Most studies have focused on exchanges between plants (Chertow and Park, 2016; Kastner et al., 2015; Notarnicola et al., 2016) or companies (Dong et al., 2013), although some recent IS studies have moved toward examining flows inside the plants (Kuznetsova et al., 2016; Pan et al., 2016; Wu et al., 2016).

While there has been a trend in IS towards including data at plant and unit operation level, process integration studies are extending their scope to include data at the cluster level. For

<sup>\*</sup> Corresponding author.

E-mail address: [s.noori@tudelft.nl](mailto:s.noori@tudelft.nl) (S. Noori).

**Acronyms and symbols**

ABC	Absorption Chiller
ABP	Anode Baking Plant
AHP	Absorption Heat Pump
AHT	Absorption Heat Transfer
ARP	Aluminium Refining Plant
CBP	Cold Briquetting Plant
CCM	Continuous Casting Machine
COP	Coefficient of performance
CW	Concentrated Water
DRI	Direct Reduced Iron
DRP	Direct Reduction Plant
EAF	Electric Arc Furnace
EL	Electricity
FF	Fossil Fuel
GPP	Gas turbine power plant
HEX	Heat Exchanger
HRSG	Heat Recovery Steam Generator
IW	Industrial Water
M	Mega
MHP	Mechanical Heat Pump

NG	Natural Gas
ORC	Organic Rankine Cycle
PGC	Other Power Generation Cycle
RO	Reverse Osmosis
SMP	Steelmaking Plant
SPL	Spent Pot Lining
SW	Sea Water
t	tonne
TSA	Total Site Analysis
WH	Waste Heat
WHR	Waste Heat Recovery
AAC	Almahdi Aluminium Complex
HOS	Hormozgan Steel Complex
HPP	Hormoz Power Plant
ISIPO	Iran Small Industries and Industrial Parks Organization
PGM	PGSEZ Management
PGSEZ	Persian Gulf Mining and Metals Special Economic Zone
SAB	Persian Gulf Saba Steel Company
SKS	Kish South Kaveh Steel Company

instance, Total Site Analysis (TSA) method has extended pinch methodology to involve several processes and centralized utility systems for energy exchange (Bagajewicz and Rodera, 2000, 2002; Becker and Maréchal, 2012; Hackl and Harvey, 2013, 2014; Mian et al., 2016a, 2016b). Similarities between TSA and IS are not limited to energy networks. Examples are already available on TSA studies focusing on the material (El-Halwagi, 2013) and water integration (Savulescu and Alva-Argaez, 2013). Considering plant-level details in IS assessment, there are indications of overlap between IS and process integration methods. Common elements in definitions and system boundaries have resulted in different understandings of IS potential.

The term potential has been used along with IS in the literature, but not with a unique interpretation. Bailey and Gadd (2015) aimed to quantify the potential of IS in the low-carbon industrial manufacturing parks (LOCIMAP) project. Although the findings of the research are notable, no clear definition of commercial and physical potential and its calculation method is presented. Notarnicola et al. (2016) have inventoried potential of available wastes and potential of produced new materials, without distinguishing which one is anticipated as IS potential. Holgado et al. (2018) also proposed a method which only identifies the potential receivers and donors for IS. The only explicit definition of industrial symbiosis potential is given by Chertow et al. (2019, p.1) as “the sum of the wastes and by-products from all of the industrial facilities in a defined area that could reasonably serve as resource inputs to other processes.” Remembering that IS is an exchange among suppliers and consumers, this definition ignores the importance of the consumer side in the interaction. Herein the need for a potential definition and conceptualization emerges.

Here is also a question of how to assess IS potential in EICs while IS is not shaped yet. Chertow et al. (2019) have proposed an algorithm to determine IS potential in a city. The overall storyline of the algorithm is remarkable and is partly followed in this research. However, as they have obtained flow data from available databases, it is not clear how someone can investigate industrial units from scratch to determine IS potential. The possibility of development is

not foreseen in the algorithm as well. UNIDO (2017) has also recommended guidelines for EIP implementation from managerial, social, and technical aspects, which is more theoretic rather than practical. On the other hand, as stated above, it is crucial to look into the difference between IS and process integration approaches while determining such potential. Therefore, there is a need for an adapted solution to assess IS potential in EICs by analysing flows at different levels.

Lack of knowledge in the definition and assessment method of IS potential prompted this study. Departing from the guidelines provided by UNIDO (2017) and Chertow et al. (2019) for IS assessment, this paper systematically explores the importance of system boundaries in IS potential. In this study, IS potential refers to the overlooked technically possible recovery and reuse of wastes from one plant as a resource to a neighbouring one in the EIC. The paper assesses the impact of plant-level details and cluster development approach on IS potential in EICs. The method is applied in the context of Iron and steel industry on the case of Persian Gulf Mining and Metals Special Economic Zone, Iran. The paper is structured as follows. Section 2 introduces the case study, section 3 describes the methods, and section 4 presents the results for each step of the research. Finally, Section 5 states the contribution of this research to the IS field and provides recommendations for future studies.

## 2. The case study

One of the growing industries in emerging economies is iron and steel, which is also among the most energy-intensive ones. This industry accounts for approximately 10% and 17% of industrial energy use in OECD and non-OECD countries, respectively (Conti et al., 2016). Steel production also results in a wide range of air pollutants, contaminated wastewater and solid wastes (Villar et al., 2012). World crude steel production has increased by a factor of two over the last thirty years, driven by a steep increase in steel production in emerging economies and China (WSA, 2019). Economic pressure and the carbon tax on energy-intensive sectors in Europe has driven iron and steel industries to immigrate to less

strictly regulated countries (Bailey and Gadd, 2015).

IS has been examined before in the steel industry dominated clusters. For instance, Dong et al. (2013) compared the total annual symbiotic material exchange and gained economic benefit from those exchanges in three iron and steel clusters in China and Japan. Yu et al. (2015) mapped an integrated steel mill from raw material to finished product. They analysed which IS connections can contribute to CO<sub>2</sub> emission reduction more effectively. Wu et al. (2016) investigated IS evolution in an iron and steel cluster in China from 1958 to 2012 and confirmed the contribution of symbiotic energy exchange to CO<sub>2</sub> emission mitigation. Pinto et al. (2019) revealed how collaboration between the steel plants and cities could contribute to sustainable urbanization. These studies have confirmed the economic and environmental benefits of IS in the steel industry.

With 24.5 million tonnes of crude steel production, Iran ranks 11th in world crude steel production (WSA, 2019). Moreover, there are plans to increase this capacity up to 55 million tonnes in the near future (Financial Tribune) despite the current sanctions, water scarcity (Madani, 2014; Madani et al., 2016) and high CO<sub>2</sub> emissions in the country (Global Carbon Project, 2016). Literature has barely studied IS cases in Iran. We looked for academic papers that included Industrial Symbiosis and Iran in the title, abstract, or keywords resulted in only one article in which Vahidi et al. (2018) listed available solid wastes for exchange in Alborz industrial state through field study. No evidence was found for implementing the findings of that research. Publicly available governmental reports, as well as websites of Iran Small Industries and Industrial Parks Organization (ISIPO) and the Ministry of Industry, Mine, and Trade, were also checked and no institution was observed governing IS concept.

Here, PGSEZ was used as a case study to illustrate IS potential in EICs. PGSEZ was founded in 1998 to facilitate domestic and foreign investment in energy-intensive industries and turn into a hub of steel, aluminium, mineral and oil products (PGSEZ, 2020) because of proximity to the South Pars, which is one of the largest natural gas reservoirs in the world. PGSEZ is one of the few clusters in Iran, in which several big metal processing industries are located. Besides, the researchers could gather original filed data from this cluster. The cluster has a governmental management team, which is under direct administration of the Iranian Mines and Mining Industries Development and Renovation Organization (IMIDRO). PGSEZ is located in the south of Iran, 14 km west of Bandar Abbas. The area is approximately 5000 ha, 2000 ha of which are operational and another 3000 ha are under preparation for future development. For the location of the cluster and companies, refer to Appendix A (Fig. A1). Currently, the cluster includes one aluminium production company (AAC), three steel production companies (HOS, SAB, and SKS), and a gas turbine power plant, recently commissioned. (PGSEZ, 2020). An under-construction pelletizing plant was not included in the existing structure of the cluster but taken into account as part of the development plan. Besides, two small zinc production and scrap melting companies, with the capacity of almost one-tenth of other companies, are also located in the cluster. Two companies, which operate independently and have no technical or managerial interaction with the other companies or cluster manager, are not included in this study.

MIDREX is a gas-based direct reduction technology to convert iron oxide into Direct Reduced Iron (DRI). Iran produces the highest amount of DRI through natural gas based MIDREX process worldwide MIDREX. In a Steelmaking Plant (SMP), DRI from Direct

Reduction Plant (DRP) is melted with scrap in an Electric Arc Furnace (EAF), and then it is shaped in a continuous casting machine. 90% of Iran's crude steel is produced through this route (WSA, 2019), in HOS and SKS as well. SKS has another SMP under construction. SAB has one DRP, recently commissioned and planned to reach the design capacity by the end of 2020. AAC produces aluminium ingots in the Hall–Héroult process, which is the dominant industrial process for smelting aluminium. An anode baking plant provides the required anode for the smelting process. Table 1 gives an overview of the companies, plants and their current capacities.

### 3. Materials and methods

A bottom-up approach was taken in this study. The method of the study is summarized in Fig. 1. First, building blocks of the cluster were identified (Section 3.1), inputs and outputs in each block were specified and combined in a comprehensive cluster block diagram (Section 3.2), material and energy input-output diagram of the whole cluster was generated, and available sources and sinks were determined (Section 3.3). Then, in order to find higher quality or quantity of sources, waste streams were traced back at plant-level for processes such as cooling, separation, and mixing before disposal (Section 3.4). Finally, IS potential was estimated matching between sinks and sources (Section 3.5).

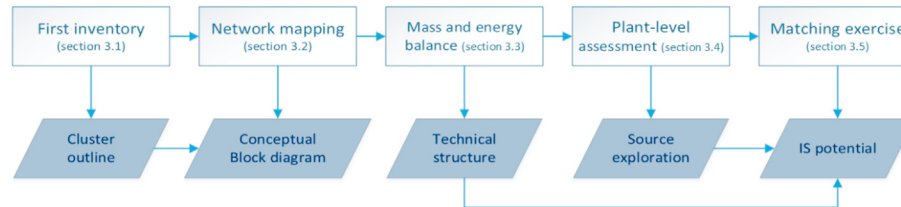
The research was carried out in 2018 in Iran and the Netherlands. Field data was gathered through semi-structured interviews. Interviews were conducted in Farsi with the development and planning manager of the cluster and with operation managers of the plants. AAC management did not allow technical data gathering in the field, therefore only general characteristics were collected via interviews with the operation manager and energy manager of the plants. The electricity supply structure of the cluster was mapped according to the data collected during interviews and complemented with information from a study of the electricity network of the PGSEZ (Monenco group, 2017).

#### 3.1. First inventory

As stated in section 1, a cluster includes companies, which might have one or several production and utility plants. We considered production plants (P) and utility plants (U) as building blocks of the cluster. The list of active companies, production plants, and their operating capacities was obtained from the cluster and company websites, national reports, google maps, and catalogues. When daily capacity was available, the annual capacity was calculated based on the actual plant working days per year considering regular maintenance and unforeseen interruptions. Since energy supply to residential areas is also one of the proven successful forms of IS (e.g., Bechara et al., 2008; Jacobsen, 2006; Korhonen and Snäkin, 2005), the population of neighbouring residential areas (R) were also gathered from official reports. This information was verified, and complemented through site visits and semi-structured interviews (spring and summer 2018). Then, we mapped all building blocks together to create the cluster outline as schematically illustrated in Fig. 2. Cluster, company, and utility infrastructure boundaries are shown in this outline. Production and utility plants inside each company are displayed as boxed named P<sub>i</sub> or U<sub>j</sub>. To make the outline more structured, similar plants in different companies are shown below each other. Residential areas are outside the cluster boundaries.

**Table 1**  
Companies and plants in the PGSEZ cluster and their operating capacities in 2018.

Company	Plant	Operating Capacity
Kish South Kaveh Steel Company (SKS)	Direct Reduction Plant (DRP)	1,850,000 t/year ( <a href="http://sksco.ir/">sksco.ir/</a> )
	Steelmaking Plant (SMP)	1,200,000 t/year
Hormozgan Steel Complex (HOS)	Direct Reduction Plant (DRP)	1,650,000 t/year ( <a href="http://hosco.ir/">hosco.ir/</a> )
	Steelmaking Plant (SMP)	1,500,000 t/year
	Cold Briquetting Plant (CBP)	57,600 t/year
Persian Gulf Saba Steel Company (SAB)	Direct Reduction Plant (DRP)	1,000,000 t/year ( <a href="http://sabasteel.co">sabasteel.co</a> )
Almahdi Aluminium Complex (AAC)	Aluminium Refining Plant (ARP)	172,000 t/year ( <a href="http://almahdi.ir/">almahdi.ir/</a> )
	Anode Baking Plant (ABP)	93,000 t/year
Hormoz Power Plant (HPP)	Gas turbine power plant (GPP)	160 MW ( <a href="http://pgsez.ir/">pgsez.ir/</a> )



**Fig. 1.** Method of the study and outcomes of each step.

### 3.2. Network mapping

Once the building blocks of the cluster were identified, material and energy flows to and from each block were investigated to generate plant input-output diagrams. Flows were grouped into three main categories: material, energy, and water (Kastner et al., 2015). When a stream mattered both in mass and energy balance, its energy and material content were considered as two separate flows. Electricity (EL), fossil fuels (FF), and waste heat (WH) were assumed as energy flows while non-energy-carrier streams were regarded as material flows (Kuznetsova et al., 2016). Waste heat was defined as unintended rejected heat from the plant (Brückner et al., 2015; Oluleye et al., 2016) and classified to three temperature levels: low-grade heat (less than 100 °C), medium-grade heat (100–400 °C) and high-grade heat (more than 400 °C). As heat recovery from solid materials is not technically easy, only waste heat from liquid and gas streams was taken into account in this paper.

Besides the main product, a plant can generate co-products (with an economic value close to the main product), by-products (lower economic value), and waste (little or zero economic value) (Horne and Matthews, 2004). The definition of co-product, by-product, and waste is based on their value for the plant, which might vary in different organizations or countries (Kuznetsova et al., 2016). Therefore, we have included them all under the category of by-products to refer to the material outflows, which are not the primary aim of the production plant. Thus, feedstock, main product, and by-product shaped three categories of material flow in this study.

Materials with a flow rate lower than 1% (compared to the main product) were ignored unless literature or field investigation indicated the presence of hazardous or valuable components in it. In the case study, water is used only as a cooling fluid, not as feedstock to the processes. Based on the water specification, we identified three categories of water: seawater (SW) taken from the

Gulf to the RO plants, industrial water (IW) used in the cooling systems, and concentrated water (CW) discharged from RO or production plants to the Gulf.

Finally, an input-output diagram for each building block of the cluster was generated and flows between the blocks were mapped. The resulting diagram is referred to as the conceptual block diagram of the cluster. Material, energy, and water flows were depicted with different colours and named as M-i, E-j and W-k respectively where i, j, and k starts from 1. Code, description, network, category, temperature range (for waste heat), origin, and destination of each flow were recorded as well. In this case, the origin or destination of each flow was identified as market, sea, air, waste disposal or other plants in the cluster. A data set of all flows' characteristics was generated for further analysis.

### 3.3. Material and energy balance

#### 3.3.1. Data gathering

One of the prominent difficulties in data gathering for IS is that flow rates of waste energy and materials are not usually measured or recorded as they are not essential for the plant. Fig. 3 shows the data gathering and verification procedure of this research. To gather actual operating data of the plants, interviews with the management of different plants were conducted. The block diagrams of each plant were given to the interviewees to provide flow data based on the operational condition of each plant. In parallel, available official reports, plant design data, operation data of plants with similar technology, and academic literature were also reviewed. If the required data was not obtainable from these sources, it was calculated or estimated based on available information. Wherever possible, gathered data from different sources were compared for verification purposes.

#### 3.3.2. Calculation

In this step, the annual rate of all listed flows was calculated



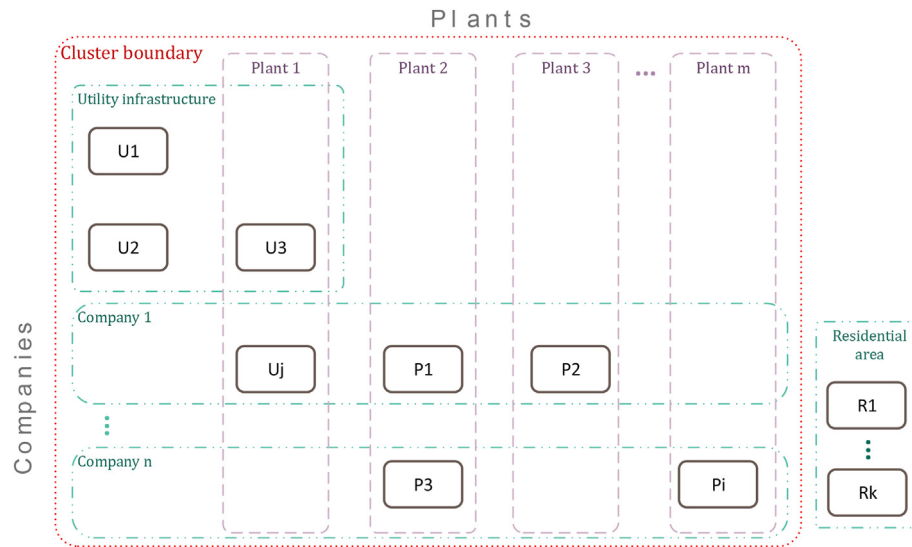


Fig. 2. Schematic diagram for a cluster outline showing cluster boundaries, companies, plants, and residential areas.

based on gathered field data. When needed, the thermodynamic properties of the substances were used (Green and Perry, 2008). If only a range for temperature or flowrate was available, the mean was assumed. If gathered field data was not sufficient to calculate the energy content of a flow, it was estimated based on literature or average world data for similar plants. Field data tables in Appendix D (Table D1, D2 and D3) give more details on each flow.

All energy flows were calculated in MW. Waste stream temperature in each plant was obtained from field data and compared with literature for verification. Theoretically, available heat of waste streams, regardless of technical limitations, was calculated using the average temperature and flow rate. When such data was not available, waste heat was estimated based on plant efficiency or literature. Once all energy flows were estimated, all supplied electricity and fossil fuel from the market to the cluster were summed up to obtain the total energy input. The energy outputs from the cluster to the market or the environment were in the form of either electricity or waste heat. Total theoretical waste heat in each temperature level was calculated separately.

The annual material flow rates were calculated in tonnes. The ratio of feedstock or by-product to the main product was obtained from the field data. When actual field data was not available, the ratios were estimated based on literature. By multiplying the ratios with the yearly production rates, the annual tonnages were estimated for each material flow in the data set. Overall material balance calculations were conducted to check the inputs and outputs of each plant. Calculated annual flow rates were listed in the data set as well. Materials with similar properties were added together. Material inputs were defined as the flows originating outside the cluster. The outputs not supplied to the market were considered as available sources for material exchange.

### 3.4. Plant level assessment

In preceding steps, a cluster technical structure has been generated to identify waste material and energy flows that were not utilized inside the cluster. Those streams were the sources for

IS. Any processing on the waste flows before disposal was investigated to understand whether considering plant-level details affects the IS potential. For instance, if flue gases were cooled down before exhaust because of environmental limitations. If so, we calculated the energy content of the waste flow before processing to check if a higher source for exchange is available. For this purpose, plant-level block diagrams, including unit operations, were generated. Waste material and energy flows were traced back among unit operations, particularly for processes such as mixing, splitting and cooling taking place before releasing the flow into the environment. When field data was not available, temperatures and flow rates were estimated based on the literature. Then, available IS sources were estimated and compared with those obtained in section 3.3 to understand how moving the system boundaries affects the IS potential.

### 3.5. Matching exercise

Waste recovery matters only if there is a consumer for it (Bailey and Gadd, 2015). As explained at the beginning of section 3, the potential consumer is referred to as a sink in this paper. In this stage, we looked for the sinks in the literature, regardless of whether the consumer already exists in the EIC. Afterward, a matching exercise between sources and sinks, inside and outside the cluster boundaries, was conducted. Like the other sections, energy and material flows were studied separately for simplicity purposes.

#### 3.5.1. Energy exchange

Energy exchange potential is part of theoretically available waste heat, which is recoverable according to technology and demand limitations (Brückner et al., 2015). A wide range of technologies is offered in literature to recover waste heat in the form of power, heating, or cooling (Huang et al., 2017; Jouhara et al., 2018; Oluleye et al., 2015, 2016; Reddy, 2013). The real performance of Waste Heat Recovery (WHR) technology is the ratio of useful output to input waste heat and work (Brückner et al., 2015), which

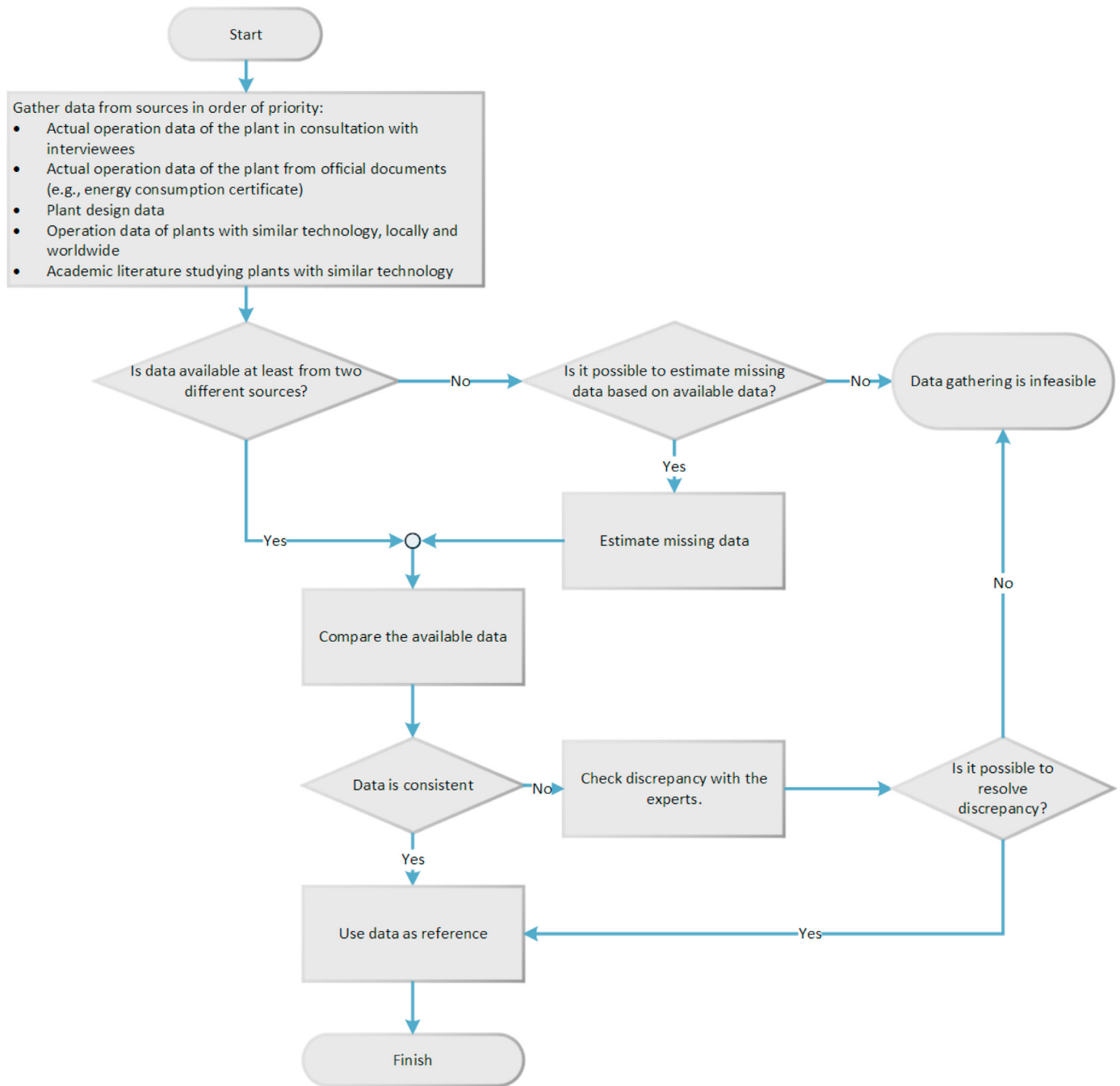


Fig. 3. Flow data gathering and verification procedure of the research.

depends on the source and sink temperature. Oluleye et al. (2017) evaluated the deviation of real performance from the ideal performance for six common industrial WHR technologies and developed a selection framework based on waste heat temperature for temperatures lower than 265 °C. Other studies suggest heat recovery via a heat exchanger or power generation from high-grade waste heat (Huang et al., 2017; Jouhara et al., 2018; Reddy, 2013). In this paper, the framework by Oluleye et al. (2017) was adopted to

select the most suitable technology. Accordingly, technologies in each temperature range are ranked by numbers in Appendix B (Table B1). More technologies are available to recover energy from medium-grade waste heat.

To identify suitable types of technologies, we looked first at whether current energy flows could be replaced with recovered energy from waste heat. Then using the quantity and temperature of available waste heat, a suitable technology was selected from

**Appendix B** considering the source temperature and demand type. The energy exchange potential was estimated by multiplying the performance of technology (from literature) with the amount of available waste heat. Then, we estimated the energy exchange potential of each waste flow through first ranked technology to examine how cluster demand affects IS potential.

### 3.5.2. Material exchange

Material exchange potential is defined here as the part of available by-products which can be recovered to be used as feedstock for other plants. Once the list of unused by-products was generated, literature was reviewed to find potential applications for each by-product. Possibilities for material use were not as broad as energy. We listed the plants that can utilize by-products as feedstock and categorized them into existing and new plants. Material exchange potential among existing plants in the cluster and with other probable plants was estimated and compared.

## 4. Results

### 4.1. Cluster outline

During the first inventory, production plants in each company; water, and electricity supply plants; operation capacity of the plants; and neighbouring residential areas were identified. Water is supplied to the cluster through three water intake units alongside the sea that are utilized by PGM, HOS, and SKS. Seawater is then treated in RO desalination plants. Natural Gas (NG) and electricity are the current main energy sources in the cluster. NG is supplied to PGSEZ via pipeline from the South Pars field. The only power plant within the cluster boundaries is a 160 MW gas turbine power plant. The cluster purchases excess electricity demand from the grid. A 400/230 kV sub-station connects HOS, SKS, and SAB to the grid. Electricity to AAC is supplied from the Hormozgan power plant directly. The residential areas just outside the cluster boundaries have 1350 households. Furthermore, 177,000 households are in Bandar Abbas (within a 14-km distance from the cluster).

### 4.2. Conceptual block diagram

The cluster block diagram with all input and output flows is presented in Fig. 4. This block diagram reveals the existing connections within and between the plants as well as unutilized material, energy, and water streams. Three steel companies collaborate with the cluster management for water and energy supply. AAC did not collaborate with the cluster management or the other companies. There was only one by-product exchange between HOS and SKS, and one water exchange connection between SKS and SAB, both intermittent. Site investigation identified an extra capacity of around 5000 tonnes per year for HOS CBP. SKS has used this capacity to convert part of its produced DRI dust to cold briquette iron. There is also a pipeline connecting SAB to the SKS desalination plant to supply water from SKS in case of emergency. Inside the companies, two by-product recycling were identified. In HOS, produced dust in DRP was reused as feedstock to CBP. In AAC, unused anode butt was sent back to ABP for reuse. Furthermore, there was no connection between the cluster and residential areas. Regarding emissions, stack gases from different plants were emitted to the air, concentrated water from desalination and production plants were sent back to the sea, and solid by-products were dumped in open areas inside the cluster.

### 4.3. Technical structure

Annual flow rates of all feedstock, main products, and by-products of the cluster are presented in Fig. 5-a. From the total material input going into the cluster, 50% was converted to main products, 33% was wasted in the form of gaseous products and 17% as solid by-products. The main material inputs to the cluster were iron oxide pellet, natural gas, alumina, lime, and ferroalloys. Billet, slab, hot briquette iron and aluminium ingot were the main products of the cluster. Gaseous by-products were generated mainly because of reduction processes. Roughly, 1.35 Mt of solid by-products were generated in the cluster, half of which was EAF slag. The other solid by-products were iron oxide dust (16%), CCM scale (14%), DRI dust (10%), EAF dust (2%), CCM losses (4%), and SPL (less than 1%).

Energy inputs to the cluster were electricity, natural gas, and coke. Waste energy flows were categorized according to their temperature level. Fig. 5-b depicts the energy input-output of the cluster. From almost 1410 MW energy input to the cluster in the form of electricity or natural gas, 578 MW was wasted in the flue gases. The recently commissioned gas turbine power plant lost 330 MW as high-grade waste heat. Exhaust gases from MIDREX, anode baking, and Hall-Heroult processes contained about 208 MW medium-grade waste heat. Steelmaking flue gas carried only 40 MW low-grade waste heat because hot gases generated in the melting unit were cooled down and mixed with low-temperature gases before being emitted into the atmosphere. The remaining 832 MW of input energy was consumed for plant energy demand or unknown wastes.

As stated in section 3.2, in PGSEZ, water was used only for cooling and scrubbing in the plant, not as reactant or feedstock. Therefore, the water network was investigated only for utility sharing opportunities. As illustrated in Fig. 5-c, the cluster consumed about 7.8 million m<sup>3</sup> of IW per year as make-up water to compensate evaporation losses in cooling towers, blow-down, and other losses in the water circulation systems from which 1.7 Mm<sup>3</sup> was supplied to SAB directly from the regional water company. To produce remained IW, RO plants required 21.9 Mm<sup>3</sup> SW from the Gulf yearly. The RO plants recover only around 30–35% of intake SW. 14.9 Mm<sup>3</sup> CW from RO plants plus 3.3 Mm<sup>3</sup> CW from water circulating systems was discharged back to the Gulf. Note that neither the cluster management nor the individual plants had installed industrial water treatment systems to recover and reuse it. SKS has installed a wastewater treatment plant project, which is currently in its last stage of construction. A comparison of the installed capacity with the demand showed that SKS and HOS had extra desalination capacity. The total installed capacity of the RO units was 14.4 million m<sup>3</sup> of IW per year. It means that in full capacity these units can release more than 30 million m<sup>3</sup> of CW to the Gulf each year. CW contains chemicals added to the water during the treatment process, but there was no monitoring of the quality of water disposed to the sea.

### 4.4. Source exploration

For simplicity purposes, we performed this step only for SMP and DRP to investigate the influence of considering plant-level details to estimate the IS potential.

#### 4.4.1. Steelmaking plant

A plant-level block diagram of SMP (P2 and P4), including unit



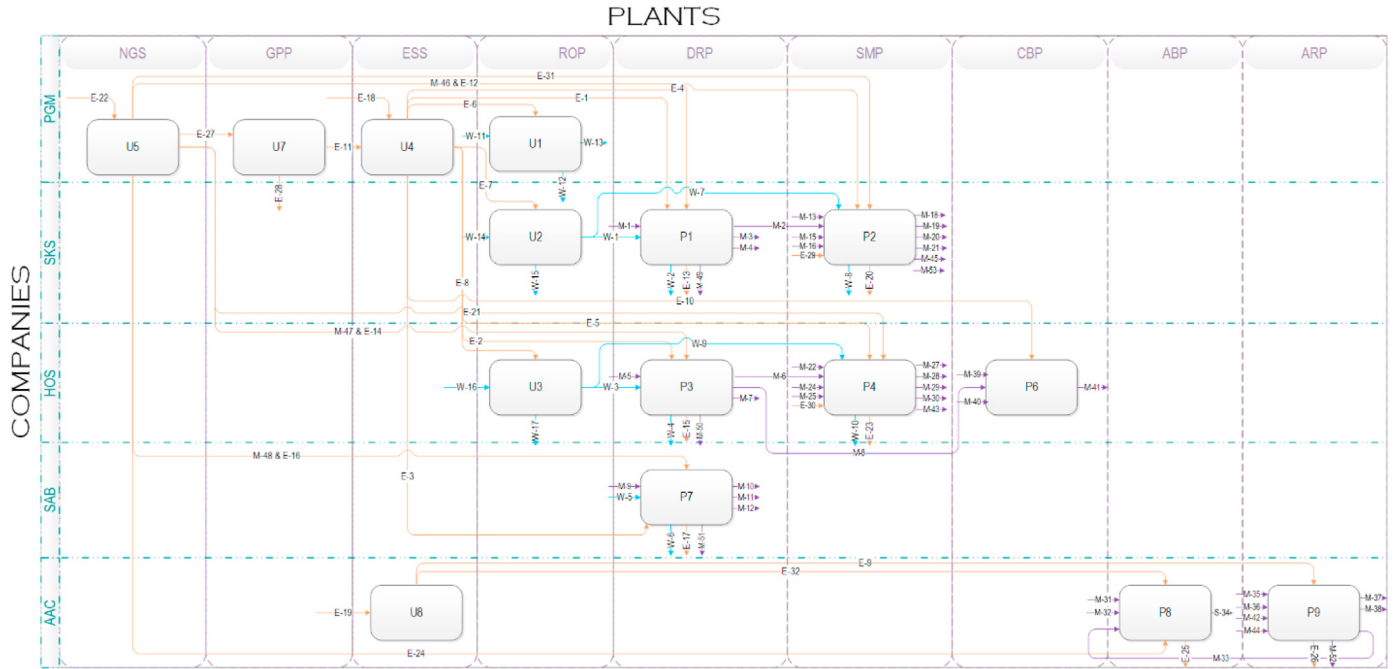


Fig. 4. PGSEZ block diagram including companies, plants, and material, energy, and water flows to and from each plant.

operations and material, energy, and water flows between them is presented in Appendix C (Figs. C1 and C2). Flue gas from the melting unit goes through a gas treatment unit before it is emitted from the stack. In the gas treatment unit, the EAF flue gas, with an average temperature around 1100 °C (Kirschen et al., 2001; Pfeifer et al., 2005), is cooled down, mixed with collected dusty air from melting hall, and then filtered to remove dust. Literature indicates that, depending on the operating condition, 15–35% of the energy input to an EAF is lost in the flue gas (Barati, 2010; Kirschen et al., 2011; Wang et al., 2016). This would mean that flue gas from P2 & P4 carries 85 MW high-grade energy before the gas treatment unit while 40 MW low-grade waste heat was estimated in this paper at plant outputs (when the plant is assessed as a black box). In modern steelmaking processes, hot flue gas stream preheats the scrap before charging to EAF (Toulouevski and Zinurov, 2017; Villar et al., 2012). This energy can also be utilized for other purposes such as input in waste heat boilers (Steinparzer et al., 2012). The plant-level block diagram showed no mixing, splitting, purifying, or other operations on the by-products before disposal; therefore, in this case, the sources of IS for material exchange did not change by the plant-level investigation.

#### 4.4.2. Direct reduction plant

A plant-level block diagram of the DRP was generated based on literature (Atsushi et al., 2010; Sarkar et al., 2018) and interviews to track waste energy and by-product flow inside the plant (Appendix C, Figs. C3 and C4). This diagram revealed that combustion flue gas is currently mixed with ambient air before going to the stack. Therefore, heat could in fact be recovered from the flue gas at a higher temperature before mixing. This temperature was around 450 °C according to the field data. Utilizing the waste heat flow for IS before mixing offers 130 MW high-grade waste heat from P1, P3, and P7 instead of 130 MW medium-grade waste heat which was observed in section 4.3. No change in available by-products from DRP was recorded by investigating plant-level block diagram. Fig. 6 compares the theoretically available waste heat for symbiotic

exchange obtained from two approaches: the traditional input-output approach and studying plant-level details. Including plant-level details results in an increase of both the quality and quantity of available energy for exchange.

#### 4.5. IS potential

##### 4.5.1. Energy exchange

Waste energy can be recovered in the form of power, heating, or cooling. Energy exchange potential depends on the demanded energy form by the consumers and the efficiency of used WHR technology. For instance, Organic Rankine Cycle (ORC) is a choice for electricity recovery for heat source temperature up to 340 °C with efficiencies of around 10% at 90 °C, 17% at 150 °C, and 27% at 300 °C (Oluleye et al., 2016).

Energy exchange potential of each waste flow was estimated first, considering current cluster demands then, based on the first ranked technology from Appendix B. The results are compared in Table 2. No domestic heating or cooling was anticipated in the existing structure of the cluster. Therefore, for cluster demand, we assumed energy recovery in the form of electricity, resulting in 157 MW power from plant output waste flows or 187 MW power considering plant-level details.

As per Appendix B, regardless of cluster demand limitations, the first ranked WHR technology for waste heats from 70 to 180 °C is the absorption chiller. Energy recovery in the form of cooling was not suggested for waste heat at higher than 180 °C due to working fluid limitations (Oluleye et al., 2017). A wide range of heat exchangers such as Heat Recovery Steam Generator (HRSG), economizer, plate heat exchanger, and boiler are available for energy recovery in the form of heating (Huang et al., 2017; Jouhara et al., 2018; Reddy, 2013). We assumed an average efficiency of 80% for heat exchangers (Jouhara et al., 2018). As per calculations in Table 2, the first ranked technologies could recover 118 MW cooling plus 368 MW heating from plant output waste flows or 90 MW cooling plus 436 MW heating taking into account plant-level details. These

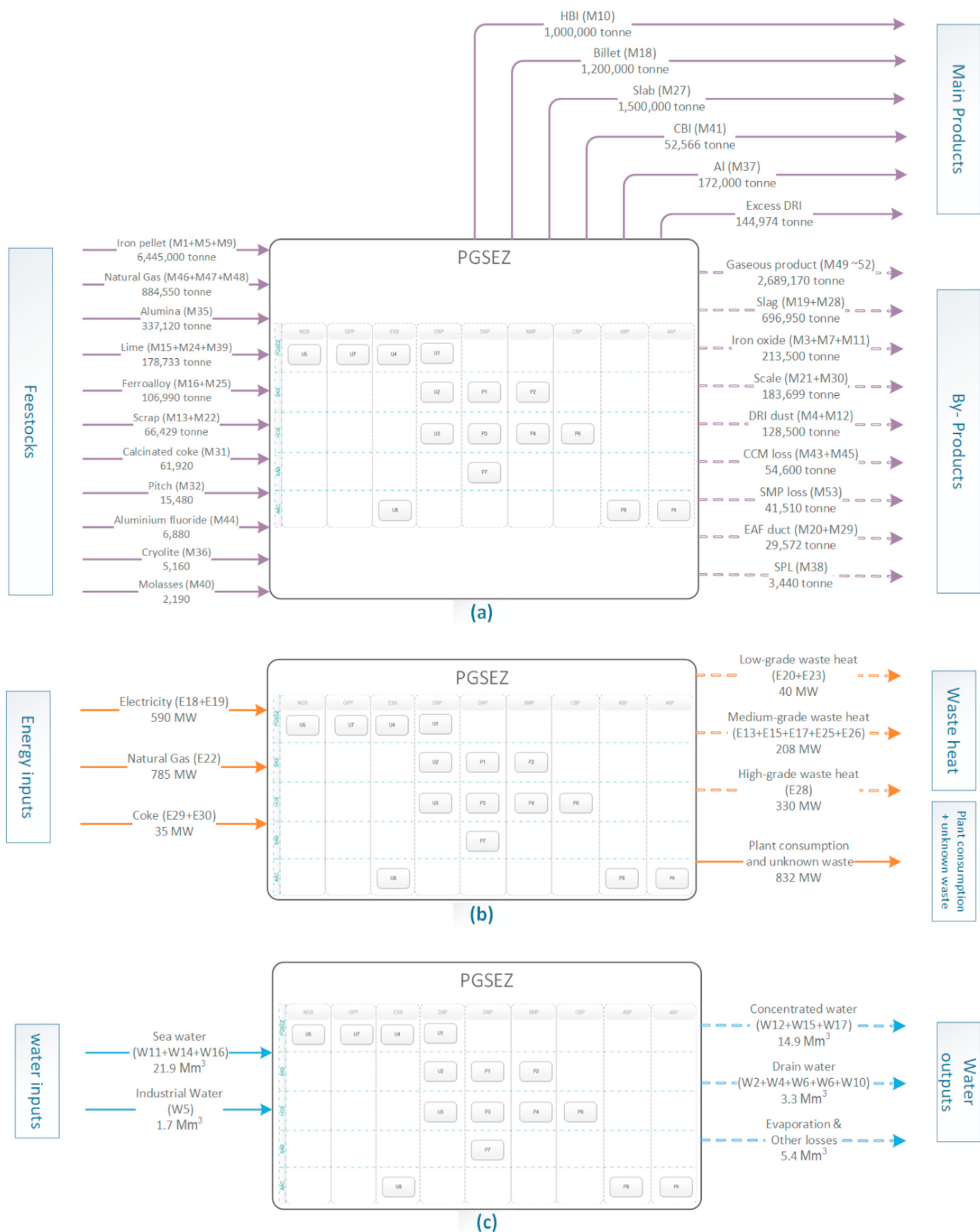
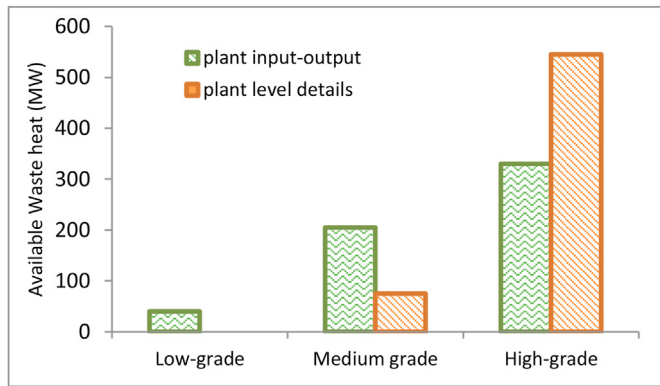


Fig. 5. (a) Material input-output, (b) Energy input-output and, (c) Water input-output of the PGSEZ cluster.



**Fig. 6.** Comparison of total available waste heat with different approaches to flows in SMP and DRP.

estimations, although rough, give an overview of energy exchange potential without requiring detailed engineering calculations. For instance, the average household electricity consumption in Iran is about 3000 kWh per year (iea, 2018), 30% of which is used for cooling (Moradi et al., 2013). Bandar Abbas with 177,000 households (Statistical Centre of Iran, 2018) has around 17.7 MW cooling demand which could be obtained from low-grade waste heat from PGSEZ.

#### 4.5.2. Material exchange

Recovery potentials of each by-product are summarized in Error! Reference source not found. Possible applications in the current structure of the cluster are indicated in a separate column. The results show limited potential for material recovery inside the cluster. Recycling CCM losses in EAF does not fall in IS exchange as it occurs within the same plant. Processing DRI dust in existing cold briquetting is limited since HOS has only ten percent extra capacity. Therefore, the only material exchange potential among existing plants is to recover iron oxide sludge as feedstock to the pelletizing plant which is under construction now.

The last column in Table 3 shows other type of industrial plants that theoretically could use by-products generated in the cluster. EAF slag is composed of FeOx, Al<sub>2</sub>O<sub>3</sub>, CaO, SiO<sub>2</sub>, and MgO. It may also contain phosphorus, chromium, and zinc oxides. Depending on the composition, EAF slag could be used in the asphalt mix (Skaf et al., 2017), or construction material (Márkus and Grega, 2007). EAF dust contains Fe, Zn, Mg, Mn, Si, and Pb (Yu et al., 2011). Dust with high zinc content is categorized in hazardous wastes (De Araújo and Schalch, 2014) and requires zinc removal before reuse (Lobato et al., 2015). Various treatment methods have been examined for this purpose (Hui-gang Wang et al., 2016; Yu et al., 2011). Literature shows the use of low zinc content dust in red ceramic (Vieira et al., 2013), glass-ceramic (Nazari et al., 2018), and cement mixture (Alsheyab and Khedaywi, 2013). CCM scale is generated as a result of oxidation of steel surface during continues casting (Lobato et al., 2015). These oxides could be reduced by carbon (Martín et al., 2009) or hydrogen (Azad, 2006). SPL (Spent Pot

**Table 2**

Comparison of energy recovery potential of waste heat streams considering cluster demand and first ranked technology.

	Available waste heat (MW)	Temperature (°C)	Energy exchange potential (MW)			
			Cluster demand		1st ranked technology	
			Amount	Form	Amount	Form
Plant input-output	40	90	4 <sup>a</sup>	electricity	28 <sup>b</sup>	cooling
	75	150	13 <sup>c</sup>	electricity	90 <sup>d</sup>	cooling
	130	300	35 <sup>e</sup>	electricity	104 <sup>g</sup>	heating
	330	500	106 <sup>f</sup>	electricity	264 <sup>g</sup>	heating
Plant-level details	75	150	13 <sup>c</sup>	electricity	90 <sup>d</sup>	cooling
	130	450	42 <sup>f</sup>	electricity	104 <sup>g</sup>	heating
	330	500	106 <sup>f</sup>	electricity	264 <sup>g</sup>	heating
	85	1100	27 <sup>f</sup>	electricity	68 <sup>g</sup>	heating

<sup>a</sup> ORC efficiency for low-temperature input heat was assumed 10% (Oluleye et al., 2016).

<sup>b</sup> Single-stage absorption chiller COP was assumed 0.7 (Reddy, 2013).

<sup>c</sup> ORC efficiency was assumed 17% (Oluleye et al., 2016).

<sup>d</sup> Double stage absorption chiller COP was assumed 1.2 (Reddy, 2013).

<sup>e</sup> ORC efficiency was assumed 27% (Oluleye et al., 2016).

<sup>f</sup> The efficiency of the HRSG plus steam turbine is assumed 32% (Ahmed et al., 2018).

<sup>g</sup> The average efficiency of heat recovery heat exchangers was considered 80% (Jouhara et al., 2018).

**Table 3**

Material recovery potential inside and outside PGSEZ boundaries.

Type	Approx. production (t/year)	SINKS	
		Inside cluster boundaries	Outside cluster boundaries
EAF slag	697,000	—	Asphalt (Skaf et al., 2017), construction (Márkus and Grega, 2007)
EAF dust	30,000	—	Zinc recovery (Hui-gang Wang et al., 2016; Yu et al., 2011), glass-ceramic (Lobato et al., 2015; Nazari et al., 2018), red ceramic (Vieira et al., 2013)
CCM scale	80,000	—	Reduction by hydrogen (Azad, 2006), reduction by carbon (Martín et al., 2009)
CCM losses	200,000	Recycle in EAF	—
SPL	3440	Steelmaking (Meirelles et al., 2014; Parhi, 2014)	Cement (Parhi, 2014; Personnet, 2013), Red brick (Miksa et al., 2003)
Iron oxide sludge	213,000	Pelletizing	—
DRI dust	128,000	—	Cold briquetting

Lining) is generated through the replacement of aluminium smelting cell cathodes (Birry et al., 2016). SPL contains leachable fluoride and cyanide compounds, thus categorized as hazardous waste (Breault et al., 2011). Literature shows the possibility of using SPL as an additive in SMP to improve slag formation (Meirelles et al., 2014; Parhi, 2014). SPL has also been recycled as raw material to cement plants (Personnet, 2013). Mikša et al. (2003) examined the use of SPL in red brick manufacturing. Solid by-products generated in DRP are iron oxide dust and DRI dust. Within three DRPs inside the cluster, only HOS has a cold briquetting plant. Another cold briquetting plant could be installed in the cluster to recover DRI dust as an input material to SMP.

This approach can improve IS opportunities in the future development of the cluster through diversity. The role of diversity in IS collaboration has been acknowledged in the literature as well. Van Berkel (2010) recognized diversity, not only in input and output flows but also in actors and their interdependencies, as a cornerstone to apply natural ecosystem principals into industrial ecosystems. Bailey and Gadd (2015) argued that stable and effective IS shapes among diverse industries. This study showed in a real case that restricting IS studies to the demand inside the cluster diminishes the IS potential while having a development approach to the cluster results in larger potentials.

An important challenge in IS research is data availability as IS looks for unutilized by-products and waste energy in the cluster while these flows are generally not monitored or even measured in many plants as they are considered of less importance for plant operation. This study shows the importance of monitoring waste flows within the plant boundaries as this results in larger IS potentials. The IS potential gives an overview of type and quantity of generated by-products and their possible application in other plants. Detailed engineering and economic analysis can then be used to select the proper recovery method. This shows a strong need for collaboration between IS researchers and plant designers.

It should, however, be noted that collaboration between industries for symbiotic exchange is entwined with social interactions. The successful emergence of IS in a cluster needs both opportunities for material and energy exchange as well as opportunities for collaboration. Technically possible symbiotic exchanges will in fact be sustained by institutional capacity (Tudor et al., 2007), economic drivers (Roberts, 2004) and social connections between the entities (Yu et al., 2014). Understanding the social structure of EICs is needed to reveal economic and institutional drivers and barriers for IS implementation. As this study focused on the technical potential in IS, those aspects were not considered in this analysis. Further research is, therefore, needed to investigate the social potential of IS. Assessing technical and social aspects together will lead to a better understanding of IS contribution to sustainable industrial development.

## 5. Conclusions

This paper assessed IS potential in EICs. It presented a systematic method to identify IS potential by developing the conceptual block diagram and analyzing the flows at different levels. Then, examined it in a case study: The Persian Gulf mining and metal industries special economic zone, Iran. Implementation of the method in the case study verifies its applicability. Moreover, as literature has rarely investigated IS cases in the Middle East, this study provides insight for future regional comparative studies. The paper adds value to the fields of process integration and IS by addressing the overlap between them and presenting the benefits of combining two approaches. Method transparency makes the research reproducible in other cases.

The key knowledge gap leading this research was the current

ambiguity in IS potential and the way it is assessed in the literature. This paper showed that considering the plant as a black box and only studying its input-output flows results in an underestimation of energy exchange sources and a lower IS potential. By investigating the flows between unit operations inside steelmaking and direct reduction plants, IS could make use of the energy content of the flue gases before cooling due to environmental regulations, which could result in not only an 8% increase in the amount of available waste heat but also shifting its quality toward high-grade waste heat. Contrary to energy flows, the plant-level assessment did not change the amount and quality of available material flows for exchange in this case study.

Examining waste recovery possibilities outside the cluster boundaries offered a higher IS potential. Although all available waste heat could be recovered to meet part of electricity demand inside the cluster, this is not the most efficient way of energy recovery. For instance, low-grade waste heat from industry could be utilized for residential cooling in hot regions. In the case study, waste heat could be used to satisfy 118 MW cooling plus 368 MW heating. A similar conclusion applies to available waste heat from the plant-level assessment.

In the clusters dominated by a particular industry, IS potential is restricted due to limited types of inflow and outflow. In this cluster, less than 20% of generated by-products are recoverable in existing plants. When examining possibilities outside the cluster, additional opportunities for material recovery were found. For example, by-products of this steel-dominated cluster could be used in cement, brick, and ceramic plants. These results show that IS approach provides new insights for EIC development policies by introducing new plants, which can utilize waste flows generated in the existing plants.

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## CRediT authorship contribution statement

**Shiva Noori:** Conceptualization, Methodology, Formal analysis, Investigation, Resources, Data curation, Writing - original draft, Visualization. **Gijsbert Korevaar:** Conceptualization, Methodology, Validation, Investigation, Writing - review & editing, Supervision. **Andrea Ramirez Ramirez:** Conceptualization, Methodology, Validation, Investigation, Writing - review & editing, Supervision, Project administration.

## Declaration of competing interest

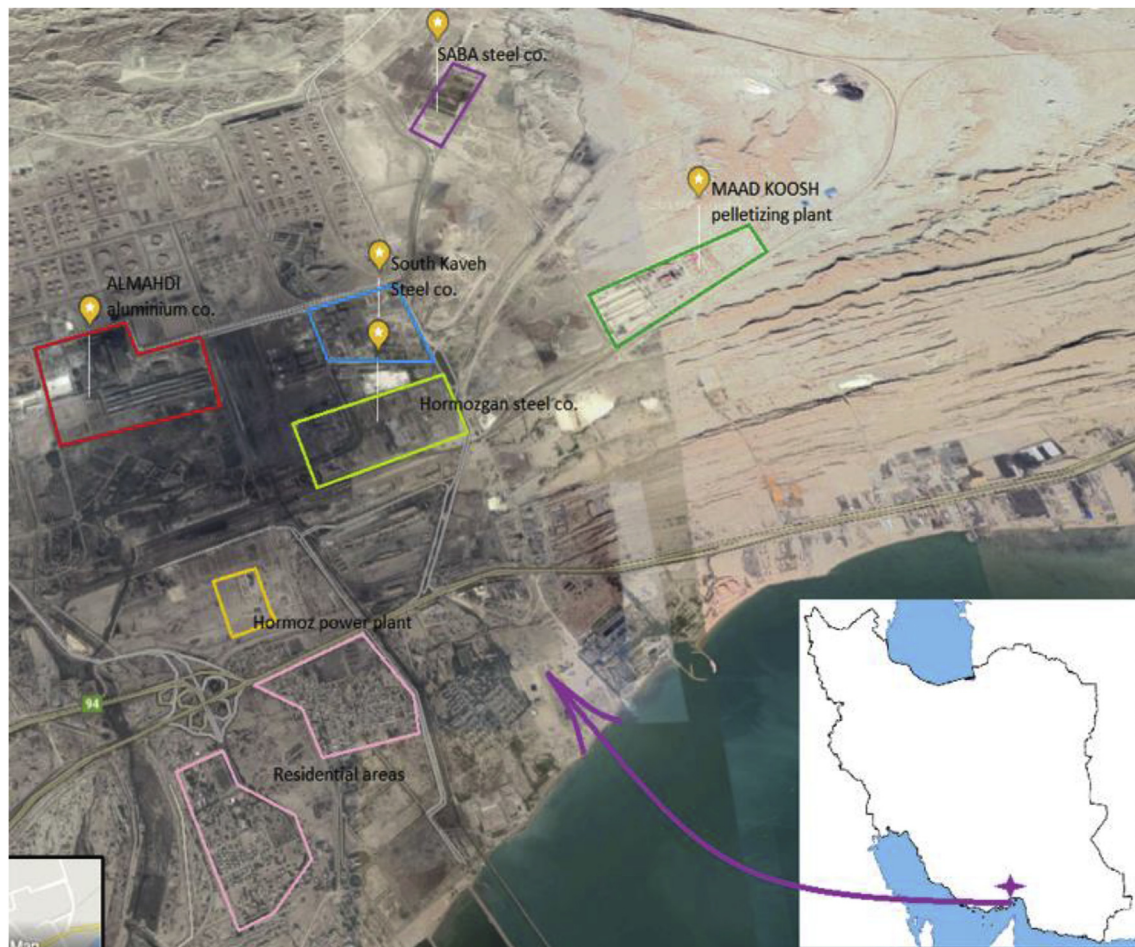
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Appendix A. Location and Schematic Map of the PGSEZ





**Fig. A1.** Location and schematic map of the PGSEZ

Source: <https://www.google.nl/maps>

## Appendix B. Waste heat Recovery Technology Ranking

## Appendix C. Input-Output block diagram and Plant-Level Block Diagram of Steelmaking and Direct Reduction Plants

**Table B1**

Ranking of Waste Heat Recovery technologies in different temperatures (In each row, number 1 is the most efficient technology in that temperature range) (Huang et al., 2017; Jouhara et al., 2018; Oluleye et al., 2017)

			SINK					
			Chilling	Heating			Power	
			ABC	AHP	AHT	HEX	MHP	ORC
SOURCE	Low grade	<70 °C				1	2	
		70 °C–100 °C	1		4	3		2
Med. grade		100 °C–140 °C	1	2			4	3
		140 °C–180 °C	1			2	3	4
		180 °C–200 °C				1		2
		200 °C–265 °C				1		2
		265 °C–400 °C				1		
High grade		>400 °C				1		
								1

**Technologies:** ABC: Absorption Chiller; AHP: Absorption Heat Pump; AHT: Absorption Heat Transfer; HEX: Heat Exchanger; MHP: Mechanical Heat Pump; ORC: Organic Rankine Cycle; PGC: other Power Generation Cycle.



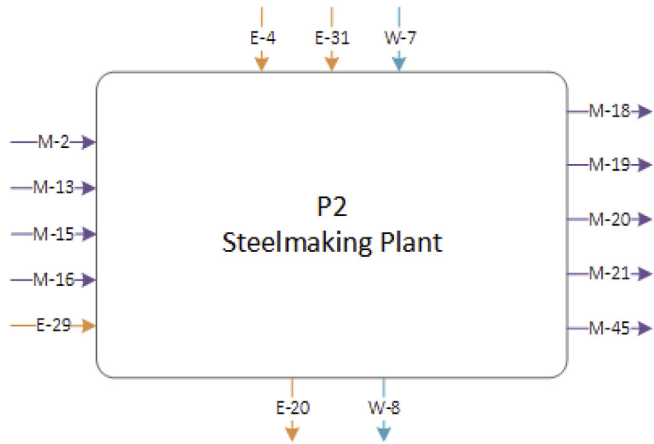


Fig. C1. Input-Output diagram of Steelmaking Plant

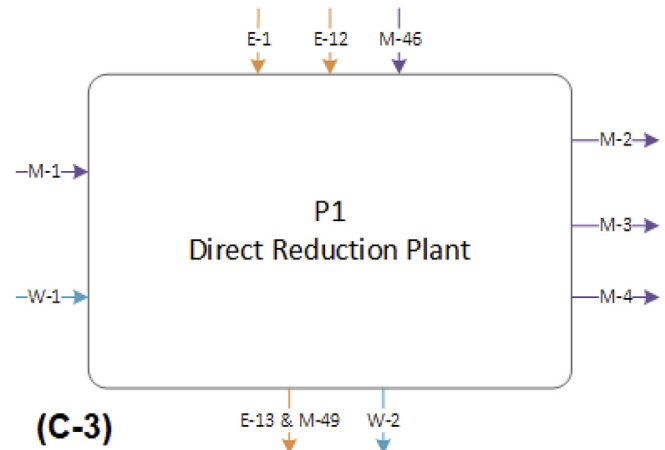


Fig. C3. Input-Output diagram of Direct Reduction Plant

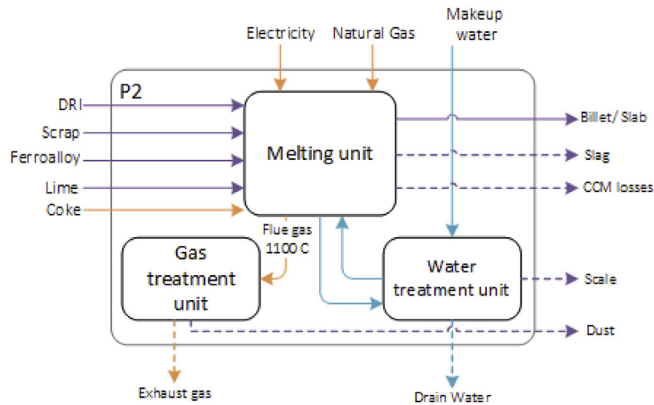


Fig. C2. Plant-level block diagram of Steelmaking Plant

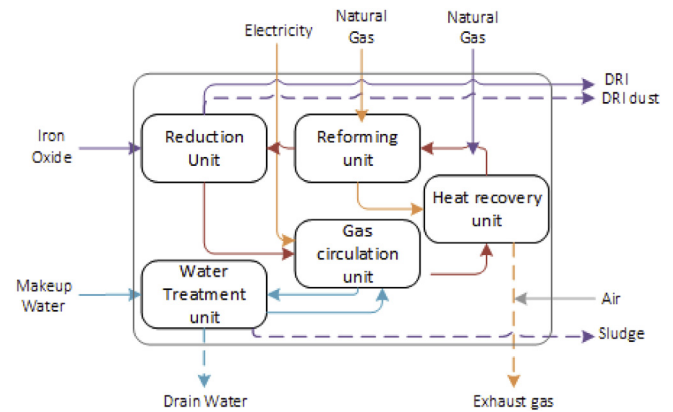


Fig. C4. Plant-level block diagram of Direct Reduction Plant

#### Appendix D. Annual Input/Output Flowrates in 2018 based on the field data

**Table D1**

Calculated annual material flows in the PGSEZ in 2018

Company	Plant	Code	Description	Type	From	To	Annual rate (t)	Field data	Calculation notes
<b>SKS</b>	DRP	M-1	Iron pellet	FS	MT	P1	2,682,500	1,45 t/t product	In agreement with literature (1,45 t/t product ( <a href="#">Sarkar et al., 2018</a> ))
<b>SKS</b>	DRP	M-2	DRI	MP	P1	P2	1,850,000	1,850,000 t/year	
<b>SKS</b>	DRP	M-3	Sludge DRI	BP	P1	WD	92,500	5% of final product	Calculated from plant material balance
<b>SKS</b>	DRP	M-4	Dust DRI	BP	P1	WD	111,000	6% of final product	
<b>SKS</b>	DRP	M-49	Gaseous products	BP	P1	AR	995,744		
<b>SKS</b>	DRP	M-46	Natural Gas	FS	U5	P1	366,744	290–300 Nm <sup>3</sup> /t product	84% of input NG used as process gas ( <a href="#">Sarkar et al., 2018</a> )
<b>HOS</b>	DRP	M-5	Iron pellet	FS	MT	P3	2,392,500	1,45 t/t product	In agreement with literature (1,45 t/t product ( <a href="#">Sarkar et al., 2018</a> ))
<b>HOS</b>	DRP	M-6	DRI	MP	P3	P4	1,650,000	1,650,000 t/year	
<b>HOS</b>	DRP	M-7	Sludge DRI	BP	P3	WD	99,000	6% of final product	Calculated from plant material balance
<b>HOS</b>	DRP	M-8	Dust DRI	BP	P3	P6	49,500	3% of final product	
<b>HOS</b>	DRP	M-50	Gaseous products	BP	P3	AR	924,990		
<b>HOS</b>	DRP	M-47	Natural Gas	FS	U5	P3	330,990	295 Nm <sup>3</sup> /t product	84% of input NG used as process gas ( <a href="#">Sarkar et al., 2018</a> )
<b>SAB</b>	DRP	M-9	Iron pellet	FS	MT	P7	1,370,000	1,37 t/t product	In agreement with literature (1,45 t/t product ( <a href="#">Sarkar et al., 2018</a> )) Plant production capacity at 2019
<b>SAB</b>	DRP	M-10	HBI	MP	P7	MT	1,000,000	1,000,000 t/year	
<b>SAB</b>	DRP	M-11	Sludge DRI	BP	P7	WD	22,000	2,2% of final product	Calculated from plant material balance
<b>SAB</b>	DRP	M-12	Dust DRI	BP	P7	WD	17,500	1,75% of final product	
<b>SAB</b>	DRP	M-51	Gaseous products	BP	P7	AR	517,316		
<b>SAB</b>	DRP	M-48	Natural Gas	FS	U5	P7	186,816	277,9 Nm <sup>3</sup> /t product	84% of input NG used as process gas ( <a href="#">Sarkar et al., 2018</a> )
<b>SKS</b>	SMP	M-13	Scrap	FS	MT	P2	22,041	18 kg/t product	Calculated from plant material balance
<b>SKS</b>	SMP	M-14	DRI	FS	P1	P2	1,506,122	1,23 t/t product	
<b>SKS</b>	SMP	M-15	Lime	FS	MT	P2	84,490	69 kg/t product	Calculated from plant material balance
<b>SKS</b>	SMP	M-16	Ferroalloys	FS	MT	P2	30,000	25 kg/t product	
<b>SKS</b>	SMP	M-18	Billet	MP	P2	MT	1,200,000	1,200,000 t/year	Calculated from plant material balance
<b>SKS</b>	SMP	M-19	Slag	BP	P2	WD	306,122	250 kg/t product	
<b>SKS</b>	SMP	M-20	Dust SMP	BP	P2	WD	11,020	9 kg/t product	Calculated from plant material balance
<b>SKS</b>	SMP	M-21	Sludge SMP	BP	P2	WD	60,000	0,05 t/t product	
<b>SKS</b>	SMP	M-45	CCM Losses	BP	P2	WD	24,000	2% of product	Calculated from plant material balance
<b>SKS</b>	SMP	M-53	Other SMP losses	BP	P2	WD	41,510		
<b>HOS</b>	SMP	M-22	Scrap	FS	MT	P4	44,388	30 kg/t product	Calculated from plant material balance
<b>HOS</b>	SMP	M-23	DRI	FS	P3	P4	1,848,980	1,23 t/t product	
<b>HOS</b>	SMP	M-24	Lime	FS	MT	P4	93,367	62 kg/t product	Calculated from plant material balance
<b>HOS</b>	SMP	M-25	Ferroalloys	FS	MT	P4	76,990	51 kg/t product	
<b>HOS</b>	SMP	M-27	Slab	MP	P4	MT	1,500,000	1,500,000 t/year	Calculated from plant material balance
<b>HOS</b>	SMP	M-28	Slag	BP	P4	WD	390,828	261 kg/t product	
<b>HOS</b>	SMP	M-29	Dust SMP	BP	P4	WD	18,552	12 kg/t product	Calculated from plant material balance
<b>HOS</b>	SMP	M-30	Sludge SMP	BP	P4	WD	123,669	0,08 t/t product	
<b>HOS</b>	SMP	M-43	CCM Losses	BP	P4	WD	30,600	2% of product	Calculated from plant material balance
<b>AAC</b>	ABP	M-31	Calcined Coke	FS	MT	P8	61,920		
<b>AAC</b>	ABP	M-32	Pitch	FS	MT	P8	15,480		
<b>AAC</b>	ABP	M-33	Spent Anode	FS	P9	P8	25,800		
<b>AAC</b>	ABP	M-34	Baked Anode	MP	P8	P9	103,200		

Table D1 (continued)

Company	Plant	Code	Description	Type	From	To	Annual rate (t)	Field data	Calculation notes
AAC	ARP	M-35	Alumina	FS	MT	P9	337,120	1,96 t/t product	
AAC	ARP	M-36	Cryolite	FS	MT	P9	5160		Estimated based on literature (30 kg/t product (Balomenos et al., 2011))
AAC	ARP	M-44	Aluminium fluoride	FS	MT	P9	6880		Estimated based on literature (40 kg/t product (Balomenos et al., 2011))
AAC	ARP	M-42	Anode	FS	P8	P9	77,400		Estimated based on literature (0,45 net t/t product (Balomenos et al., 2011))
AAC	ARP	M-37	Aluminium ingot	MP	P9	MT	172,000	172,000 t/year	
AAC	ARP	M-38	SPL (Spent Pot Lines)	BP	P9	WD	3440		Estimated based on literature (0,02 kg/kg product (Balomenos et al., 2011))
AAC	ARP	M-52	Gaseous products	BP	P9	AR	244,240		Estimated based on literature (1,53 kg/kg product (Balomenos et al., 2011))
HOS	CBP	M-39	Lime	FS	MT	P6	876	0,2 t/h	
HOS	CBP	M-40	Molasses	FS	MT	P6	2190	0,5 t/h	
HOS	CBP	M-41	CBI	MP	P6	MT	52,566	12 t/h	
PGM	NGS	M-17	Natural Gas	FS	MT	U5	884,550		Calculated based on cluster material balance.

Table D2

Calculated energy flows in the PGSEZ in 2018

Company	Plant	Code	Description	Type	From	To	Energy (MW)	Field data	Calculation notes
SKS	DRP	E-1	Electricity	EL	U4	P1	33,4	120–130 kWh/t product	In agreement with literature (Worrell et al., 2007)
SKS	DRP	E-12	Natural Gas	FF	U5	P1	112,5	290–300 Nm <sup>3</sup> /t product	<ul style="list-style-type: none"> <li>Matches with literature. 16% of input NG used as fuel gas (Sarkar et al., 2018)</li> <li>Heating value NG = 33.4 MJ/Nm<sup>3</sup> (Nazari and Maleki, 2008)</li> </ul>
SKS	DRP	E-13	Exhaust Gas-M	WH	P1	AR	52,2	500,000 m <sup>3</sup> /h per module Temperature = 300 °C	Ambient temperature = 27 °C (Weather atlas, 2019)
HOS	DRP	E-2	Electricity	EL	U4	P3	27,0	118 kWh/t product	In agreement with literature (Worrell et al., 2007)
HOS	DRP	E-14	Natural Gas	FF	U5	P3	100,4	295 Nm <sup>3</sup> /t product	<ul style="list-style-type: none"> <li>Matches with literature. 16% of input NG used as fuel gas (Sarkar et al., 2018)</li> <li>Heating value NG = 33.4 MJ/Nm<sup>3</sup> (Nazari and Maleki, 2008)</li> </ul>
HOS	DRP	E-15	Exhaust gas	WH	P3	AR	49,1	483,000 m <sup>3</sup> /h per module Temperature = 300 °C	Ambient temperature = 27 °C (Weather atlas, 2019)
SAB	DRP	E-3	Electricity	EL	U4	P7	19,4	139,8 kWh/t product	In agreement with literature (Worrell et al., 2007)
SAB	DRP	E-16	Natural Gas	FF	U5	P7	57,3	278 Nm <sup>3</sup> /t product	<ul style="list-style-type: none"> <li>In agreement with literature. 16% of input NG used as fuel gas (Sarkar et al., 2018)</li> <li>Heating value NG = 33.4 MJ/Nm<sup>3</sup> (Nazari and Maleki, 2008)</li> </ul>
SAB	DRP	E-17	Exhaust gas	WH	P7	AR	28,5	15 kg/t product	Data was not available. 4200 m <sup>3</sup> /t product assumed such as other DRPs.
SKS	SMP	E-29	Coke	FF	MT	P2	22,8	750 kWh/t product	Heating value C = 32.8 MJ/kg (Green and Perry, 2008)
SKS	SMP	E-4	Electricity	EL	U4	P2	125,0	5,5 Nm <sup>3</sup> /t product	In agreement with literature (Kirschen et al., 2011; Pfeifer et al., 2005)
SKS	SMP	E-31	Natural Gas	FF	U5	P2	8,5	2,000,000 Nm <sup>3</sup> /hr	Heating value NG = 33.4 MJ/Nm <sup>3</sup> (Nazari and Maleki, 2008)
SKS	SMP	E-20	Exhaust gas	WH	P2	AR	21,3	Temperature = 90 °C	Ambient temperature = 27 °C (Weather atlas, 2019)
HOS	SMP	E-30	Coke	FF	MT	P4	11,6	6 kg/t product	Heating value C = 32.8 MJ/kg (Green and Perry, 2008)
HOS	SMP	E-5	Electricity	EL	U4	P4	159,6	766 kWh/t product	In agreement with literature (Kirschen et al., 2011; Pfeifer et al., 2005)
HOS	SMP	E-21	Natural Gas	FF	U5	P4	6,4	3.3 Nm <sup>3</sup> /t product	Heating value NG = 33.4 MJ/Nm <sup>3</sup> (Nazari and Maleki, 2008)
HOS	SMP	E-23	Exhaust gas	WH	P4	AR	19,0	1,683,520 Nm <sup>3</sup> /hr Temperature = 90 °C	Ambient temperature = 27 °C (Weather atlas, 2019)
PGZ	ROP	E-6	Electricity	EL	U4	U1	0,6		Estimated based on literature (4.5 kWh/m <sup>3</sup> (Khawaji et al., 2008))
SKS	ROP	E-7	Electricity	EL	U4	U2	2,3	3,7 kWh/m <sup>3</sup> product	In agreement with literature (2–5 kWh/m <sup>3</sup> (Khawaji et al., 2008))
HOS	ROP	E-8	Electricity	EL	U4	U3	3,3	2,7 kWh/m <sup>3</sup> product	In agreement with literature (2–5 kWh/m <sup>3</sup> (Khawaji et al., 2008))
AAC	ABP	E-24	Natural Gas	FF	U5	P8	9,8		Estimated based on literature (2.45 GJ/t product (Springer and Hasanbeigi, 2016))
AAC	ABP	E-32	Electricity	EL	U8	P8	2,0		Estimated based on literature (140 kWh/t product (Springer and Hasanbeigi, 2016))
AAC	ABP	E-25	Exhaust gas	WH	P8	AR	2,2		Estimated based on the literature (Keller et al., 2010): 4000 Nm <sup>3</sup> /t anode; Temperature = 250 °C
AAC	ARP	E-9	Electricity	EL	U8	P9	377,4	15,800 kWh/t product	
AAC	ARP	E-26	Exhaust gas	WH	P9	AR	75,5		20% of energy input is considered as flue gas losses (Balomenos et al., 2011)
HOS	CBP	E-10	Electricity	EL	U4	P6	0,1	16.7 kWh/t product	
PGM	GPP	E-27	Natural Gas	FF	U5	U7	490,0	33% thermal efficiency	NG consumption calculated based on efficiency
PGM	GPP	E-28	Exhaust gas	WH	U7	AR	330	33% thermal efficiency Temperature = 500 °C	Waste heat calculated based on efficiency
PGM	GPP	E-11	Electricity	EL	U7	U4	160,0	160 MW power plant	
PGM	ESS	E-18	Electricity	EL	MT	U4	210,6	Total electricity input to HOS, SKS, SAB.	In agreement with consultant reports (Monenco group, 2017)
AAC	ESS	E-19	Electricity	EL	MT	U8	377,4	Total electricity input to AAC.	In agreement with consultant reports (Monenco group, 2017)
PGM	NGS	E-22	Natural Gas	FF	MT	U5	781,5	Total NG input to the cluster.	

**Table D3**

Calculated annual water flows in the PGSEZ in 2018

Company	Plant	Code	Description	Type	From	To	Annual rate (Nm <sup>3</sup> )	Field data	Calculation notes
SKS	DRP	W-1	Makeup water	IW	U2	P1	1,850,000	1,0 m <sup>3</sup> /t product	
SKS	DRP	W-2	Drain Water	WW	P1	SE	740,000		assumed same as HOS DRP
HOS	DRP	W-3	Makeup water	IW	U3	P3	1,485,000	1,0 m <sup>3</sup> /t product	
HOS	DRP	W-4	Drain Water	WW	P3	SE	495,000	0,3 m <sup>3</sup> /t product	
SAB	DRP	W-5	Makeup water	IW	U6	P7	1,720,000	1,72 Nm <sup>3</sup> /t product	
SAB	DRP	W-6	Drain Water	WW	P7	SE	688,000		ratio to makeup assumed same as HOS
SKS	SMP	W-7	Makeup water	IW	U2	P2	1,346,939	1,1 Nm <sup>3</sup> /t product	
SKS	SMP	W-8	Drain Water	WW	P2	SE	630,000		assumed same as HOS SMP
HOS	SMP	W-9	Makeup water	IW	U3	P4	1,395,804	0,93 Nm <sup>3</sup> /t product	
HOS	SMP	W-10	Drain Water	WW	P4	SE	787,500	0,53 Nm <sup>3</sup> /t product	
PGM	ROP	W-11	Sea Water	SW	SE	U1	3,000,000		Calculated based on 30% recovery
PGM	ROP	W-12	Concentrated Water	WW	U1	SE	2,100,000		Calculated based on 30% recovery
PGM	ROP	W-13	Industrial Water	IW	U1		900,000		Calculated considering 3000 Nm <sup>3</sup> /day and 300 working days per year
SKS	ROP	W-14	Sea Water	SW	SE	U2	10,656,463	30% recovery & process consumption	Calculated based on 30% recovery
SKS	ROP	W-15	Concentrated Water	WW	U2	SE	7,459,524	70% concentration	Calculated based on 30% recovery
SKS	ROP	W-19	total treated water	IW	U2	P1 & P2	3,196,939		Total makeup needed for SMP & DRP
HOS	ROP	W-16	Sea Water	SW	SE	U3	8,230,869		Calculated based on 35% recovery
HOS	ROP	W-17	Concentrated Water	WW	U3	SE	5,350,065		Calculated based on 35% recovery
HOS	ROP	W-18	total treated water	IW	U3	P4 & P3	2,880,804	Make up for SMP & DRP	Total make up needed for SMP & DRP

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