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

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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 (Teräsvirta, 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), while some recent IS studies have moved toward examining flows inside the plants (Kuznetssova 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
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 Marechal, 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 limited to energy networks. Examples are already available on TSA studies focusing on the material (El-Halwagi, 2013) and water integration (Savulescu and Alva-Argea, 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 CO2 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 CO2 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 CO2 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 or U. To make the outline more structured, similar plants in different companies are shown below each other. Residential areas are outside the cluster boundaries.
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
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.

### 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
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
presented in Fig. 4. This block diagram reveals the existing con-

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 feed-
stock for other plants. Once the list of unused by-products was

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 con-
nections within and between the plants as well as unutilized ma-
terial, energy, and water streams. Three steel companies

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 prod-
ucts 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

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
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 85 MW high-grade energy from P2 & P4, instead of 80 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.
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 Figure 6. 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, Al₂O₃, CaO, SiO₂, 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      | electricity | 28 | cooling |
|                         |                 | 75     | 150  | 13     | electricity | 90 | cooling |
|                         |                 | 130    | 300  | 35     | electricity | 104 | heating |
|                         |                 | 330    | 500  | 105    | electricity | 264 | heating |
|                         |                 | 75     | 150  | 13     | electricity | 90 | heating |
|                         |                 | 130    | 450  | 42     | electricity | 104 | heating |
|                         |                 | 330    | 500  | 106    | electricity | 264 | heating |
|                         |                 | 85     | 1100 | 27     | electricity | 68 | heating |

- a: ORC efficiency for low-temperature input heat was assumed 10% (Oluleye et al., 2016).
- b: Single-stage absorption chiller COP was assumed 0.7 (Reddy, 2013).
- c: ORC efficiency was assumed 17% (Oluleye et al., 2016).
- d: Double stage absorption chiller COP was assumed 1.2 (Reddy, 2013).
- e: ORC efficiency was assumed 27% (Oluleye et al., 2016).
- f: The efficiency of the HRSG plus steam turbine is assumed 32% (Ahmed et al., 2018).
- g: 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           |

Fig. 6. Comparison of total available waste heat with different approaches to flows in SMP and DRP.
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; Miksa 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
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 raw, 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     | PGC     |
| SOURCE  |          |           |         |         |         |         |         |
| Low grade | <70 °C  | 1         | 1       | 2       |         |         |         |
|         | 70 °C–100 °C | 1       | 4       | 3       | 2       |         |         |
| Med. grade | 100 °C–140 °C | 1       | 2       | 3       | 4       | 3       | 3       |
|         | 140 °C–180 °C | 1       | 2       | 3       | 4       | 2       | 2       |
|         | 180 °C–200 °C | 1       | 2       | 3       | 4       | 2       | 2       |
|         | 200 °C–265 °C | 1       | 2       | 3       | 4       | 2       | 2       |
|         | 265 °C–400 °C | 1       | 2       | 3       | 4       | 2       | 2       |
| High grade | >400 °C | 1         | 2       | 3       | 4       | 2       | 2       |

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.
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 |
|---------|------------|--------------|------|------|-----|----------------|------------|-------------------|
| SKS     | DRP D-1    | Iron pellet  | FS   | MT   | P1  | 2,682,500      | 1.45 t/t product | In agreement with literature (1.45 t/t product (Sarkar et al., 2018)) |
| SKS     | DRP D-2    | DRI          | MP   | P1   | P2  | 1,850,000      | 1,850,000 t/year |                                 |
| SKS     | DRP D-3    | Sludge DRI   | BP   | P1   | WD  | 92,500         | 5% of final product |                                 |
| SKS     | DRP D-4    | Dust DRI     | BP   | P1   | WD  | 111,000        | 6% of final product |                                 |
| SKS     | DRP M-49   | Gaseous products | BP   | P1   | AR  | 995,744        | Calculated from plant material balance |                     |
| SKS     | DRP M-46   | Natural Gas  | FS   | U5   | P1  | 366,744        | 290–300 Nm³/t product | 84% of input NG used as process gas (Sarkar et al., 2018) |
| HOS     | DRP D-5    | Iron pellet  | FS   | MT   | P3  | 2,392,500      | 1.45 t/t product | In agreement with literature (1.45 t/t product (Sarkar et al., 2018)) |
| HOS     | DRP D-6    | DRI          | MP   | P3   | P4  | 1,650,000      | 1,650,000 t/year |                                 |
| HOS     | DRP D-7    | Sludge DRI   | BP   | P3   | WD  | 99,000         | 6% of final product |                                 |
| HOS     | DRP D-8    | Dust DRI     | BP   | P3   | P6  | 49,500         | 3% of final product |                                 |
| HOS     | DRP M-47   | Natural Gas  | FS   | U5   | P3  | 330,990        | 295 Nm³/t product | 84% of input NG used as process gas (Sarkar et al., 2018) |
| SAB     | 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 (Sarkar et al., 2018)) |
| SAB     | DRP M-10   | HBI          | MP   | P7   | MT  | 1,000,000      | 1,000,000 t/year | Plant production capacity at 2019 |
| SAB     | DRP M-11   | Sludge DRI   | BP   | P7   | WD  | 22,000         | 2.2% of final product |                                 |
| SAB     | DRP M-12   | Dust DRI     | BP   | P7   | WD  | 17,500         | 1.75% of final product |                                 |
| SAB     | DRP M-51   | Gaseous products | BP   | P7   | AR  | 517,316        | Calculated from plant material balance |                     |
| SAB     | DRP M-48   | Natural Gas  | FS   | U5   | P3  | 186,816        | 277.9 Nm³/t product | 84% of input NG used as process gas (Sarkar et al., 2018) |
| SKS     | SMP M-13   | Scrap        | FS   | MT   | P2  | 22,041         | 18 kg/t product |                                 |
| SKS     | SMP M-14   | DRI          | FS   | P1   | P2  | 1,506,122      | 1.23 t/t product |                                 |
| SKS     | SMP M-15   | Lime         | FS   | MT   | P2  | 84,490         | 61 kg/t product |                                 |
| SKS     | SMP M-16   | Ferroalloys  | FS   | MT   | P2  | 30,000         | 25 kg/t product |                                 |
| SKS     | SMP M-18   | Billet       | MP   | P2   | MT  | 1,200,000      | 1,200,000 t/year |                                 |
| SKS     | SMP M-19   | Slag         | BP   | P2   | WD  | 306,122        | 250 kg/t product |                                 |
| SKS     | SMP M-20   | Dust SMP     | BP   | P2   | WD  | 11,020         | 9 kg/t product |                                 |
| SKS     | SMP M-21   | Sludge SMP   | BP   | P2   | WD  | 60,000         | 0.05 t/t product |                                 |
| SKS     | SMP M-45   | CCM Losses   | BP   | P2   | WD  | 24,000         | 2% of product |                                 |
| SKS     | SMP M-53   | Other SMP losses | BP   | P2   | WD  | 41,510         | Calculated from plant material balance |                     |
| HOS     | SMP M-22   | Scrap        | FS   | MT   | P4  | 44,388         | 30 kg/t product |                                 |
| HOS     | SMP M-23   | DRI          | FS   | P3   | P4  | 1,848,980      | 1.23 t/t product |                                 |
| HOS     | SMP M-24   | Lime         | FS   | MT   | P4  | 93,367         | 62 kg/t product |                                 |
| HOS     | SMP M-25   | Ferroalloys  | FS   | MT   | P4  | 76,990         | 51 kg/t product |                                 |
| HOS     | SMP M-27   | Slab         | MP   | P4   | MT  | 1,500,000      | 1,500,000 t/year |                                 |
| HOS     | SMP M-28   | Slag         | BP   | P4   | WD  | 390,828        | 261 kg/t product |                                 |
| HOS     | SMP M-29   | Dust SMP     | BP   | P4   | WD  | 18,552         | 12 kg/t product |                                 |
| HOS     | SMP M-30   | Sludge SMP   | BP   | P4   | WD  | 123,669        | 0.08 t/t product |                                 |
| HOS     | SMP M-43   | CCM Losses   | BP   | P4   | WD  | 30,600         | 2% of product |                                 |
| AAC     | ABP M-31   | Calcined Coke | FS   | MT   | P8  | 61,920         | 61,920 | Estimated based on literature (0.60 t/t product (Beglery et al., 2018)) |
| AAC     | ABP M-32   | Pitch        | FS   | MT   | P8  | 15,480         | 15,480 | Estimated based on literature (0.15 t/t product (Beglery et al., 2018)) |
| AAC     | ABP M-33   | Spent Anode  | FS   | P9   | P8  | 25,800         | 25,800 | Estimated based on literature (0.25 t/t product (Beglery et al., 2018)) |
| AAC     | ABP M-34   | Baked Anode  | MP   | P8   | P9  | 103,200        | 0.25 t/t product | 0.25 return anode (International Aluminium Institute, 2018) |
### Table D1 (continued)

| Company Plant Code | Description | Type | From | To | Annual rate (t) | Field data | Calculation notes |
|---------------------|-------------|------|------|----|-----------------|------------|-------------------|
| AAC                 | ARP         | M-35 | Alumina | FS | MT | 337,120 | 1,96 t/t product |
| AAC                 | ARP         | M-36 | Cryolite | FS | MT | 5160 |
| AAC                 | ARP         | M-44 | Aluminium fluoride | FS | MT | 6880 |
| AAC                 | ARP         | M-42 | Anode | FS | P8 | 77,400 |
| AAC                 | ARP         | M-37 | Aluminium ingot | MP | P9 | MT | 172,000 |
| AAC                 | ARP         | M-38 | SPL (Spent Pot Lines) | BP | P9 | WD | 4344 |
| AAC                 | ARP         | M-52 | Gaseous products | BP | P9 | AR | 244,240 |
| HOS                 | CBP         | M-39 | Lime | FS | MT | 876 | 0,2 t/h |
| HOS                 | CBP         | M-40 | Molasses | FS | MT | 2190 | 0,5 t/h |
| HOS                 | CBP         | M-41 | CBI | MP | P6 | MT | 52,566 |
| NGS                 |            | M-17 | Natural Gas | FS | MT | U5 | 884,550 |

### 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 |
| SKS                 | DRP         | E-12 | Natural Gas FF | FS | U5 | P1 | 112,5 |
| SKS                 | DRP         | E-13 | Exhaust Gas-M | WH | P1 | AR | 52,2 |
| HOS                 | DRP         | E-2  | Electricity | EL | U4 | P3 | 27,0 |
| HOS                 | DRP         | E-14 | Natural Gas FF | FS | U5 | P3 | 100,4 |
| HOS                 | DRP         | E-15 | Exhaust gas WH | P3 | AR | 49,1 |
| SAB                 | DRP         | E-3  | Electricity | EL | U4 | P7 | 19,4 |
| SAB                 | DRP         | E-16 | Natural Gas FF | FS | U5 | P7 | 57,3 |
| SAB                 | DRP         | E-17 | Exhaust gas WH | P7 | AR | 28,5 |
| SKS                 | SMP         | E-29 | Coke | FF | MT | P2 | 22,8 |
| SKS                 | SMP         | E-4  | Electricity | EL | U4 | P2 | 125,0 |
| SKS                 | SMP         | E-31 | Natural Gas FF | FS | U5 | P2 | 8,5 |
| SKS                 | SMP         | E-20 | Exhaust gas WH | P2 | AR | 21,3 |
| HOS                 | SMP         | E-30 | Coke | FF | MT | P4 | 11,6 |
| HOS                 | SMP         | E-5  | Electricity | EL | U4 | P4 | 139,6 |
| HOS                 | SMP         | E-21 | Natural Gas FF | FS | U5 | P4 | 6,4 |
| HOS                 | SMP         | E-23 | Exhaust gas WH | P4 | AR | 19,0 |
| PGZ                 | ROP         | E-6  | Electricity | EL | U4 | U1 | 0,6 |
| SKS                 | ROP         | E-7  | Electricity | EL | U4 | U2 | 2,3 |
| HOS                 | ROP         | E-8  | Electricity | EL | U4 | U3 | 3,3 |
| AAC                 | ARP         | E-24 | Natural Gas FF | FS | U5 | P8 | 9,8 |
| AAC                 | ARP         | E-32 | Electricity | EL | U8 | P8 | 2,0 |
| AAC                 | ARP         | E-25 | Exhaust gas WH | P8 | AR | 2,2 |
| AAR                 | ARP         | E-9  | Electricity | EL | U8 | P9 | 377,4 |
| AAC                 | ARP         | E-26 | Exhaust gas WH | P9 | AR | 75,5 |
| HOS                 | CBP         | E-10 | Electricity | EL | U4 | P6 | 0,1 |
| PGM                 | GPP         | E-27 | Natural Gas FF | FS | U5 | U7 | 490,0 |
| PGM                 | GPP         | E-28 | Exhaust gas WH | U7 | AR | 330 |
| PGM                 | GPP         | E-11 | Electricity | EL | U7 | U4 | 160,0 |
| PGM                 | ESS         | E-18 | Electricity | EL | MT | U4 | 210,6 |
| PCM                 | NGS         | E-19 | Electricity | EL | U8 | 377,4 |
| PCM                 | NGS         | E-22 | Natural Gas FF | MT | U5 | 781,5 |

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**Notes:**
- Estimated based on literature (30 kg/t product (Balomenos et al., 2011))
- Estimated based on literature (40 kg/t product (Balomenos et al., 2011))
- Estimated based on literature (0.45 net t/t product (Balomenos et al., 2011))
- Estimated based on literature (0.02 kg/kg product (Balomenos et al., 2011))
- Estimated based on literature (1.53 kg/kg product (Balomenos et al., 2011))
- Calculated based on cluster material balance.
Table D3

| Company Plant Code | Description Type From To | Annual rate (Nm³) | Field data | Calculation notes |
|---------------------|--------------------------|-------------------|------------|------------------|
| SKS ROP W-12 | Sea Water SW SE U1 | 2,100,000 | Calculated based on 30% recovery |
| SKS ROP W-13 | Sea Water SW SE U2 | 900,000 | Calculated considering 3000 Nm³/day and 300 working days per year |

References

Ahmed, A., Esmaeil, K.K., Irfan, M.A., Al-Mufadi, F.A., 2018. Design methodology of heat recovery steam generator in electric utility for waste heat recovery. Int. J. Low Carbon Technol. 13, 369–379. https://doi.org/10.1002/ijlct.2016045.

Alshewy, M.A.T., Khedawyi, T.S., 2013. Effect of electric arc furnace dust (EAFD) on properties of asphalt cement mixture. Resour. Conserv. Recycl. 70, 38–43. https://doi.org/10.1016/j.resconrec.2012.10.001.

Atsushi, M., Uemura, H., Sakaguchi, T., 2016. Midrex processes. Kobelco Technol. Rev. 29, 8.

Awad, M., 2006. Enviro-friendly hydrogen generation from steel mill-scale via metal-steam reforming. Bull. Sci. Technol. Soc. 26, 305–313. https://doi.org/10.1177/0270467606290710.

Bagajewicz, M., Roderer, H., 2000. Energy savings in the total site heat integration across many plants. Comput. Chem. Eng. 24, 1237–1242. https://doi.org/10.1016/S0098-1354(99)00318-5.

Bagajewicz, M., Roderer, H., 2000. Energy savings in the total site heat integration across many plants. Comput. Chem. Eng. 24, 1237–1242. https://doi.org/10.1016/S0098-1354(99)00318-5.

Balogun, M., Akinsan, D., Pasaparlis, I., 2011. Energy and exergy analysis of the primary aluminum production processes: a review on current and future sustainability. Miner. Process. Extr. Metall. Rev. 32, 69–89. https://doi.org/10.1080/08827560.2010.530721.

Barati, M., 2010. Energy intensity and greenhouse gases footprint of metallurgical processes: a continuous steelmaking case study. Energy 35, 3731–3737. https://doi.org/10.1016/j.energy.2010.05.022.

Bechara, L., Veiga, E., Magrini, A., 2008. Eco-industrial park development in Rio de Janeiro, Brazil: a tool for sustainable development. https://doi.org/10.1016/j.heliyon.2018.11.e00509.

Becker, H., Maréchal, F., 2012. Energy integration of industrial sites with heat exchange restrictions. Comput. Chem. Eng. 37, 104–118. https://doi.org/10.1016/j.compchemeng.2011.09.014.

Begley, M., Ameri Siahhoei, M., Baharvand, B., 2018. Investigating the effect of coke quality on coke oven gas consumption in anode plant. In: Iran International Aluminium Pot Lining, pp. 22–25.

Birry, B., Leclerc, S., Poirier, S., 2016. The LCL process: a sustainable solution for the treatment and recycling of spent pot lining. Light Met 2016, 467–471. https://doi.org/10.1016/j.lightmet.2016.08.001.

Breault, B.R., Poirier, S., Hamel, G., Pucci, A., 2011. A Green ‘Way to Deal with Spent Pot Lining’. pp. 22–25.

Brückner, S., Liu, S., Miró, L., Radschild, M., Faheem, I., 2015. Industrial waste heat recovery technologies: an economic analysis of heat transformation technologies. Appl. Energy 151, 157–167. https://doi.org/10.1016/j.apenergy.2015.01.147.

Chertow, M., Gordon, M., Hirsch, P., Ramaswami, A., 2019. Industrial symbiosis potential and urban infrastructure capacity in Mysuru, India. Environ. Res. Lett. 14, 75003. https://doi.org/10.1088/1748-9326/ab20ed.

Chertow, M., Park, J., 2016. Scholarship and practice in industrial symbiosis: 1899–2014. In: Taking Stock of Industrial Ecology, Springer International Publishing, Cham, pp. 87–116. https://doi.org/10.1007/978-3-319-20571-7_5.

Chertow, M.R., 2007. "Uncovering" industrial symbiosis. J. Ind. Ecol. 11, 11–30.

Conti, J., Holtberg, P., Diefenderfer, J., Angelina, L., Turnure, J.T., Westfall, L., 2016. International energy outlook 2016 with projections to 2040. https://doi.org/10.2172/1296780.

De Araújo, J.A., Schalch, V., 2014. Recycling of electric arc furnace (EAF) dust for use in steel making process. J. Mater. Res. Technol. 3, 274–279. https://doi.org/10.1016/j.jmrtec.2014.06.003.

Dong, L., Zhang, H., Fujita, T., Ohnishi, S., Li, H., Fujii, M., Dong, H., 2013. Environmental and economic gains of industrial symbiosis for Chinese iron/steel industry: Kawasaki’s experience and practice in Liu Zhou and Jianin. J. Clean. Prod. 59, 226–238. https://doi.org/10.1016/j.jclepro.2013.06.048.

Douglas, J.M., 1988. Conceptual Design of Chemical Processes. McGraw-Hill chemical engineering series. TA – TT – McGraw-Hill, New York SE – XVIII, 601 il lustrations; 22 cm.

El-Halwagi, M.M., 2013. Conserving Material Resources through Process Integration: Material Conservation Networks, Handbook of Process Integration (PI): Minimization of Energy and Water Use, Waste and Emissions. Woodhead Publishing Limited. https://doi.org/10.1533/9780857097293.1.422.

Global Carbon Project, 2016. CO2 emissions | global carbon atlas [WWW Document]. URL. http://www.globalcarbonatlas.org/en/CO2-emissions. accessed 1.14.19.

Green, D.W., Perry, R.H., 2008. Perry’s Chemical Engineers’ Handbook. McGraw-Hill Companies, Inc.

Hackl, R., Harvey, S., 2014. From heat integration targets toward implementation - a TSA (total site analysis)-based design approach for heat recovery systems in industrial clusters. Energy 90, 163–172. https://doi.org/10.1016/j.energy.2015.05.115.

Hackl, R., Harvey, S., 2013. Applying exergy and total site analysis for targeting refrigeration shaft power in industrial clusters. Energy 55, 5–14. https://doi.org/10.1016/j.energy.2013.03.029.

Holgado, M., Benedetti, M., Evans, S., Baptista, A.J., Lourenço, E.J., 2018. Industrial symbiosis implementation by leveraging on process efficiency methodologies. Procedia CIRP 69, 872–877. https://doi.org/10.1016/j.procir.2017.11.078.

Horne, R.E., Matthews, R., 2004. BIOMITRE Technical Manual. Renewable Energy, Huang, F., Zheng, J., Baleyanaud, J.M., Lu, J., 2017. Heat recovery potentials and technologies in industrial zones. J. Energy Inst. 90, 951–961. https://doi.org/10.1016/j.joei.2016.07.012.

International Aluminium Institute, 2018. Prebaked Anodes for Aluminium Electrolysis.

Jacobsen, N.B., 2006. Industrial symbiosis in Kalundborg, Denmark. J. Ind. Ecol. 10, 750–759. https://doi.org/10.1162/10881980677545411.

Jouhara, H., Khordehgah, N., Almahmoud, S., Delpech, B., Chauhan, A., Tassou, S.A., 2018. Waste heat recovery technologies and applications. Therm. Sci. Eng. Prog. 6, 268–289. https://doi.org/10.1016/j.tesep.2018.04.017.
