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REVIEW

Energy-based industrial symbiosis: a literature review for circular energy transition

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Abstract

Nowadays, industrial symbiosis (IS) is recognized as a key strategy to support the transition toward the circular economy. IS deals with the (re)use of wastes produced by a production process as a substitute for traditional production inputs of other traditionally disengaged processes. In this context, this paper provides a systematic literature review on the energy-based IS approach, i.e., IS synergies aimed at reducing the amount of energy requirement from outside industrial systems or the amount of traditional fuels used in energy production. This approach is claimed as effective aimed at reducing the use of traditional fuels in energy production, thus promoting a circular energy transition. 682 papers published between 1997 and 2018 have been collected, and energy-based IS cases have been identified among 96 of these. As a result of the literature review, three categories of symbiotic synergies have been identified: (1) energy cascade; (2) fuel replacement; and (3) bioenergy production. Through the review, different strategies to implement energy-based IS synergies are highlighted and discussed for each of the above-mentioned categories. Furthermore, drivers, barriers, and enablers of business development in energy-based IS are discussed from the technical, economic, regulatory, and institutional perspective. Accordingly, future research directions are recommended.

Keywords Industrial symbiosis · Circular economy · Energy · Energy-based industrial symbiosis · Systematic literature review

1 Introduction

The global energy consumption has more than doubled from 1960 to 2014 (Fig. 1), due to the combined effect of growth in population and in per capita energy consumption (Fig. 2), and it is continuing to grow (e.g., Ganivet 2019; Smil 2016; The World Bank 2017). In

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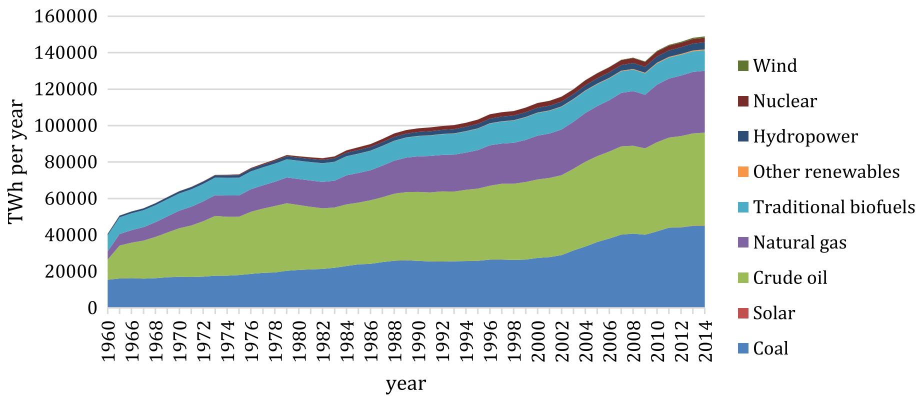

Fig. 1 Global primary energy consumption per energy source, measured in terawatt-hours (TWh) per year—adapted from Smil (2016)

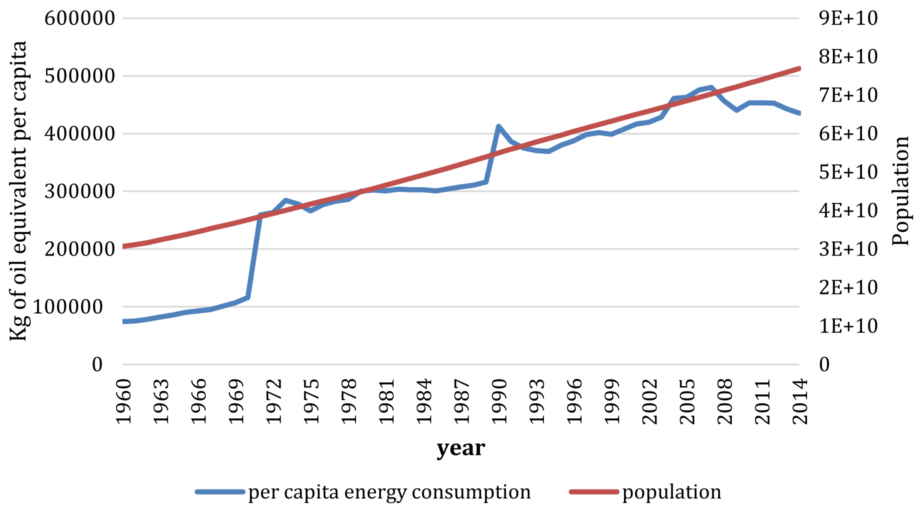

Fig. 2 Per capita energy consumption and global population from 1960 to 2014—data from The World Bank (2017)

fact, global energy demand rose by 2.1% in 2017, more than twice the growth rate in 2016, and it is expected to further rise by 30% until 2040 (International Energy Agency 2017a, b, 2018; The World Bank 2017). Currently, over 80% of the energy is produced by fossil fuels such as oil, coal, and natural gas. Such production is responsible for more than 60% of the CO_2 emissions worldwide (International Energy Agency 2017a), which are recognized as the main cause of global warming (IPCC 2014). For this reason, policymakers at the global level committed to cut CO_2 emissions by 80% until 2050 (European Commission 2011a; Rogelj et al. 2016). In order to achieve this goal, the amount of energy produced from fossil fuels must be drastically reduced.

Energy-based industrial symbiosis (IS) is recognized as an effective strategy to reduce the use of traditional fuels in energy production (Giurco et al. 2011; Hassiba et al. 2017; Liu et al. 2017). For instance, the total energy consumption of the Chinese iron and steel sector could be reduced up to 6% thanks to energy-based IS synergies (Wen et al. 2017). IS deals with the (re)use of waste materials and energy produced by a production process as a substitute for traditional production inputs of other traditionally disengaged processes, belonging to the same company or to different companies (e.g., Chertow 2000; Lombardi and Laybourn 2012; Shah et al. 2020; Yadav and Tiwari 2019). Hence, firms implementing the IS practice can reduce their production costs while creating environmental benefits for the overall collectivity (e.g., Chavalparit et al. 2006; Jacobsen 2006; Zhao et al. 2018). Benefits created by the IS practice have been recognized via adopting several methodologies based on flow analysis, thermodynamics, life cycle assessment (LCA), and network analysis (Fraccascia and Giannoccaro 2020). Since able to create economic and environmental benefits simultaneously, IS is nowadays recognized as one of the most-effective strategies supporting the transition toward the circular economy (e.g., de Abreu and Ceglia 2018; Ungerman and Dědková 2019). Recently, the implementation of IS has been explicitly recommended by the European Commission (European Commission 2011b, 2015) and several countries have introduced it in their agenda (Park et al. 2008; Van Berkel et al. 2009).

From the company perspective, the main driver toward adopting the IS practice is the willingness to gain economic benefits (Esty and Porter 1998; Yuan and Shi 2009). However, companies usually lack awareness on how to introduce the IS approach into their current business practice (Fraccascia et al. 2016). Aimed at supporting the adoption of IS, the literature provides several contributions on IS business models discussing a wide range of factors (e.g., technical, operational, logistical, spatial, regulatory, market-related, and environmental) that might influence the cooperation dynamics among companies (Chopra and Khanna 2014; Genc et al. 2019; Herczeg et al. 2018; Madsen et al. 2015; Sakr et al. 2011; Tudor et al. 2007; Yazan and Fraccascia 2020). However, so far the literature has mainly focused on material-based IS synergies, while less attention has been devoted to energy-based IS synergies, i.e., symbiotic synergies where a waste of one production process is exploited for energy-purposed by another production process. In particular, the literature has mainly explored some case studies of energy-based IS synergies. A recent article by Butturi et al. (2019) investigates how eco-industrial parks can help to promote the use of renewable energy sources via IS, at both industrial and urban levels. Despite its valuable contribution, their study does not provide a comprehensive view on energy-based IS, since it considers only eco-industrial parks, while IS can occur also among entities not belonging to the same park (e.g., Chertow 2000). Nevertheless, the authors recognize the need to perform a more in-depth analysis of the literature on energy-related themes that can support the implementation of energy symbiosis schemes. In fact, a comprehensive view of the energy-based IS approach is missing, in terms of application strategies, drivers, barriers, and enablers.

This paper aims at filling this gap. Through a systematic review of the available literature on practical cases of IS, we first frame existing and planned energy-based IS synergies. Then, based on the IS cases, we identify the different strategies to implement energy-based IS businesses and highlight the drivers, barriers, and enablers of business development in energy-based IS. Accordingly, future research directions are recommended.

The paper is structured as follows. Section 2 presents the methodology adopted to carry out the review. Sections 3 and 4 show the results of the literature review: in particular, Sect. 3 proposes a categorization of energy-based IS cases, while in Sect. 4 the drivers, barriers, and enablers of energy-based IS are elaborated. Then, a discussion follows in Sect. 5. The paper ends with conclusions in Sect. 6.

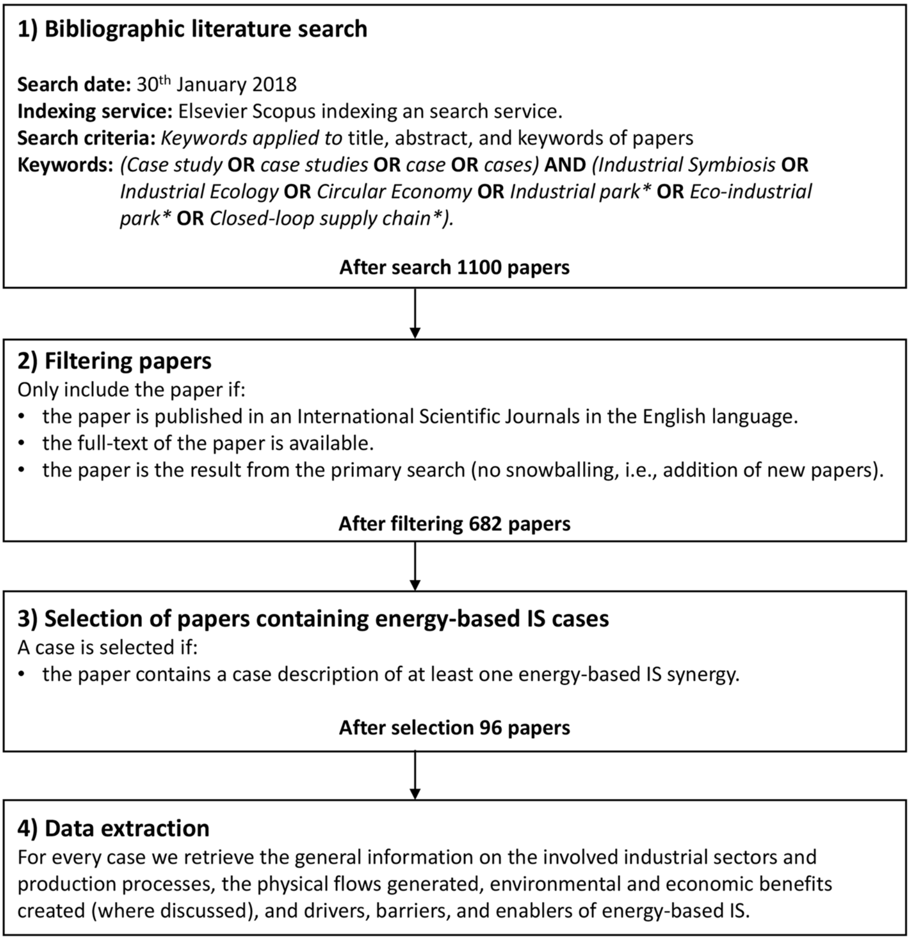

Fig. 3 Steps for the literature review

2 Methodology

The study is based on a bibliographic research conducted on January 30, 2018. Figure 3 graphically shows the steps conducted in this research. The first step was the bibliographic literature search, aimed at collecting papers presenting and discussing cases of IS. The data were retrieved from Scopus, an academic citation indexing and search service of Elsevier. The following research keywords have been applied to title, abstract, and keywords of papers:

(“*Case study*” **OR** “*case studies*” **OR** *case* **OR** *cases*) **AND** (“*Industrial Symbiosis*” **OR** “*Industrial Ecology*” **OR** “*Circular Economy*” **OR** “*Industrial park**” **OR** “*Eco-industrial park**” **OR** “*Closed-loop supply chain**”).

Research keywords were selected to encompass the concept of IS including “industrial ecology,” “circular economy,” and “closed-loop supply chain” concepts. Such an approach was adopted because, according to the authors’ experience, some papers might discuss cases of IS without contextualizing them into the IS field but within the above-mentioned

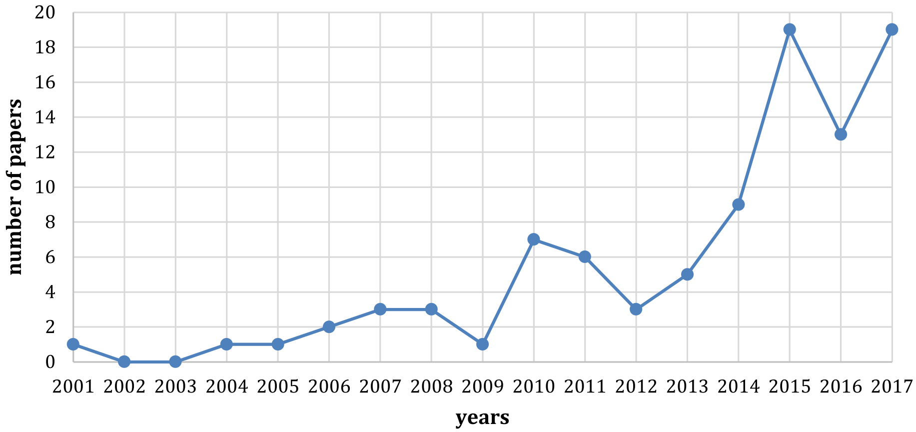

Fig. 4 Number of papers published per year (papers published in 2018 are not shown)

fields. As a result of the research, 1100 papers were collected, 1041 of them (94.64%) in English. We further limited the analysis by considering only papers published in international scientific journals, in order to focus on peer-reviewed articles (e.g., Caniato et al. 2015; Potrich et al. 2019), and papers whose full text was available. The first database was composed of 682 papers (65.80% of the original sample). The second step concerned filtering papers. In this regard, a selection process was carried out through analyzing the papers resulting from the previous step, aimed at excluding papers discussing cases not relevant for the aim of this research, i.e., cases not involving energy-based IS exchanges.[1] The third step was aimed at building the final database of papers, which includes only papers reporting at least one energy-based IS synergy. Such a database is made by 96 papers published between 2001 and 2018 in 36 journals (Fig. 4). Note that some papers may discuss more than one case of energy-based IS synergy. The final step was aimed at retrieving general information on the involved industrial sectors and production processes, the physical flows generated, the environmental and economic benefits created (where discussed), and drivers, barriers, and enablers of energy-based IS.

3 Energy-based industrial symbiosis classification

Following the systematic literature review, we categorize energy-based IS exchanges in three groups: (1) energy cascade; (2) fuel replacement; and (3) bioenergy production. In particular, an energy cascade between two processes occurs when the waste energy (e.g., waste heat or steam) produced by the former is used by the latter. A fuel replacement-based IS synergy occurs when waste materials are used to replace traditional fuels in existing fuel-based energy production processes (e.g., coal-based energy production). Finally, bioenergy production-based IS synergies are devoted to exploiting organic wastes to produce bioenergy. Figure 5 depicts the graphical representation of these categories, considering—for the sake of clarity—the case where different companies are involved.

[1] A practical case of IS might not involve energy-based IS synergies but only material-based IS synergies.

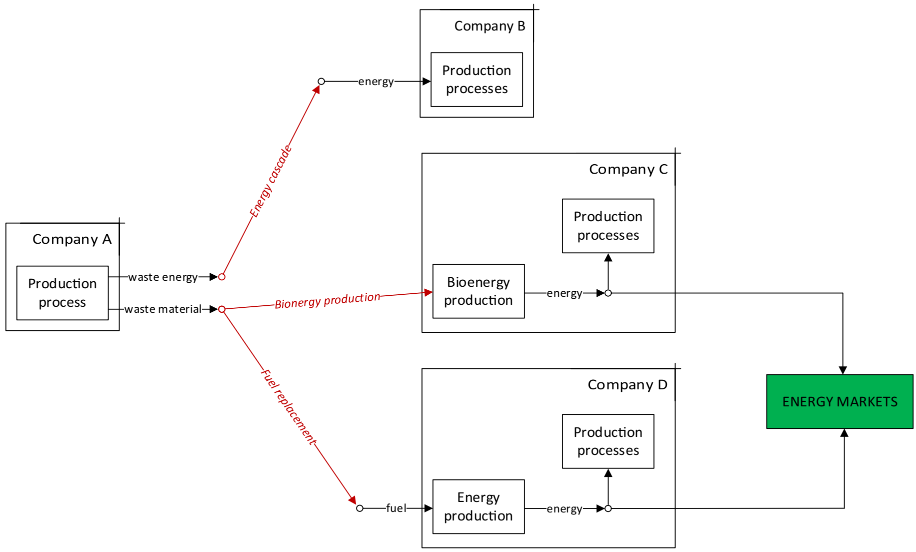

Fig. 5 Graphical scheme of energy-based IS synergies involving processes from different companies: energy cascade (between companies A and B), bioenergy production (between companies A and C), and fuel replacement (between companies A and D)

In the following subsections, each category is presented with an overview of cases, which discusses how energy-based IS synergies are implemented. This approach is mainly material/energy flows oriented, so to map the potential physical flows that might offer different sustainable and circular business opportunities to the involved companies. Technically, the IS takes place in three phases: identification of the potential of IS and potential business partners, assessment of economic and environmental expectations and development of potential business strategies, and the implementation of IS as a long term and stable business. Depending on a large variety of operational, spatial, technical, and technological conditions, each IS might show a case-specific character offering diversified pathways of business implementation. Technical aspects are discussed in detail in Sect. 4 for each of the specific energy-based IS categories proposed in this section.

3.1 Energy cascade

Four different models of energy cascade are implemented, according to business and technical dimensions (Fig. 6). From the business perspective, energy cascade can be implemented within a single company (Li et al. 2010; Zhang et al. 2013) or among different companies. From the technical perspective, energy flows can be directly implemented among production processes (Mannino et al. 2015; Yu et al. 2015a) or the energy can be sent to an energy recovery facility and then to other processes (Baas 2011; Li et al. 2015a). In all of the above-mentioned models, implementing energy cascade requires building new infrastructures, e.g., the pipelines connecting the involved processes and the heat recovery system facility (Tsvetkova et al. 2015).

From the waste energy producer's perspective, we found several types of companies and production processes involved: power plants (Kikuchi et al. 2016; Zhang et al. 2009), iron

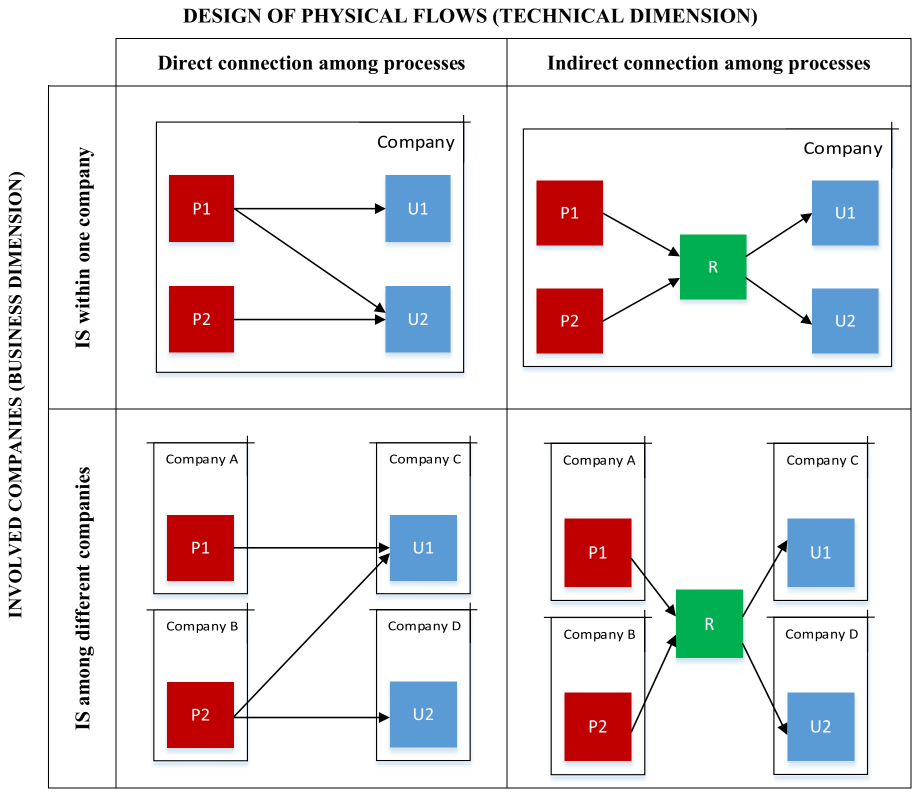

Fig. 6 Models of energy cascade IS synergies. Legend: P, energy producer; U energy user; R, energy recovery system

and steel companies (Dong et al. 2013a, b, 2014; Li et al. 2010; Li et al. 2015c; Yu et al. 2015a), pulp mills (Baas 2011; Lehtoranta et al. 2011; Sokka et al. 2011), chemical companies (Chae et al. 2010; Li et al. 2015c; Mannino et al. 2015), sugar production facilities (Short et al. 2014), biofuel producers (Martin and Eklund 2011), mineral companies (Brent et al. 2012), and glass manufacturers (Andrews and Pearce 2011). From the user perspective, different companies are currently involved in the use of waste energy: waste treatment companies (Wang et al. 2017a, b), pulp mill and paper mill factories (Li and Ma 2015; Wang et al. 2017a, b), food processing companies (Fan et al. 2017; Park and Park 2014), home appliance companies (Fan et al. 2017), chemical companies (Dong et al. 2013a; Geng et al. 2014; Li et al. 2017; Park and Park 2014; Sun et al. 2017; Yune et al. 2016), desalination facilities (Shi et al. 2010), construction companies (Zhang et al. 2009), automobile manufacturers (Shi et al. 2010), high-tech companies (Zhang et al. 2009), refineries and biofuel producers (Eckelman and Chertow 2013; Martin and Eklund 2011), community facilities and greenhouses (Baas 2011; Geng et al. 2010; Martin and Eklund 2011; Pakarinen et al. 2010; Posch 2010), steel plants and sintering plants (Wu et al. 2016a). Notice that the same company can play both the role of energy producer and energy user simultaneously, for instance when it uses high-pressure steam (which is received from another company) while also producing leftover low-pressure steam (which is sent to another company) (Li et al. 2010; Shi et al. 2010).

Implementing energy cascade allows to minimize the use of energy within industrial areas because the total energy requirement from outside is reduced, *ceteris paribus* (Leong et al. 2017; Wen et al. 2017). For instance, in Jinan City (China) the energy requirement has been reduced by 10,900 tons of coal equivalent (tce) per year thanks to energy cascade among companies located in the industrial area close to the city (Dong et al. 2014). In Liuzhou (China), 200 t/year of steam produced by a power plant and an iron and steel company is destined to the central heating of the residential sector: this allows to reduce the energy consumption by 12,500 tce (Sun et al. 2017). Furthermore, reducing energy requirement contributes to creating indirect environmental benefits in terms of avoided CO_2 emissions from energy production. For instance, reduction in CO_2 emissions thanks to energy cascade accounts for 12.6 kt/year in Liuzhou (China) (Sun et al. 2017) and 45.5 kt/year in Ulsan (South Korea) (Park and Park 2014). Several studies are devoted to assessing the benefits potentially stemming from implementing energy cascade among companies in a given area. For instance, implementing energy cascade in Guiyang (China) would allow to recover around 300 tons per year of waste heat, which corresponds to save fossil fuel by 18,864 tce per year and reduce CO_2 emissions by 49 kt/year (Dong et al. 2016; Li et al. 2015b). Zhang et al. (2016) show that the energy demand from companies located in the eco-industrial park in Jurong Island (Singapore) can be reduced by around 40%. Hassiba et al. (2017) show that implementing energy cascade among companies located in the industrial park in Mesaieed Industrial City (Qatar) might contribute to reduce energy costs by around 5 million dollars per year and CO_2 emissions by more than 200 tons per day. Finally, Chae et al. (2010) show that energy cascade in petrochemical complex in Yeosu (South Korea) can reduce waste heat by 82% and energy costs by more than 88%.

3.2 Fuel replacement

Four different models of fuel replacement synergies are implemented, according to business and technical dimensions (Fig. 7). From the business perspective, fuel replacement synergies can be implemented within one company or among different companies. From the technical perspective, the waste can be directly used to replace fuel (direct replacement) or converted in an alternative fuel, e.g., pallet (indirect replacement), through a waste treatment process.

Several types of waste are currently used as alternative fuels: lignin from pulp and paper industry or from bioethanol production (Gabriel et al. 2017; Mattila et al. 2012; Tan et al. 2016), plastic wastes (Huysman et al. 2017; Yu et al. 2015d), exhausted tires (Albino and Fraccascia 2015; Eckelman and Chertow 2013; Guo et al. 2016; Subulan et al. 2015; Yazan et al. 2018; Yu et al. 2015d), wood scraps (Baas 2011; Kikuchi et al. 2016; Meneghetti and Nardin 2012; Rosa and Beloborodko 2015; Ruggieri et al. 2016; Velenturf 2016), coal gangue generated from coal mining process (Guo et al. 2016; Li et al. 2015b), bagasse from sugar production (Kikuchi et al. 2016), solid residues from biodiesel production (Benjamin et al. 2015), carbonic oxide from calcium carbide furnace (Yu et al. 2015b), agricultural wastes produced by farms (Costa and Ferrão 2010), waste oil (Eckelman and Chertow 2013), and industrial solvents and hazardous waste (Ashton 2011). These wastes are mainly used to replace coal in heat and power plants or in energy-intensive industries (e.g., cement production).

New applications of the fuel replacement practice have also been explored, dealing with wastes that are traditionally not recovered but disposed of in the landfill. In this regard, Allesina et al. (2017) investigate the conversion of spent coffee grounds from bars into

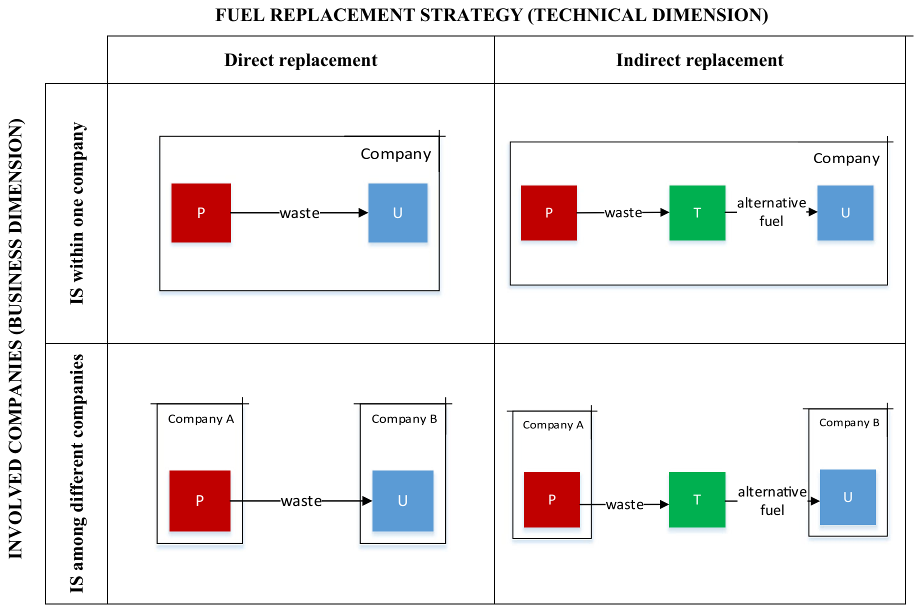

Fig. 7 Models of fuel replacement IS synergies. Legend: P, producer; U, user; T, waste treatment process

pellets, which can be used as a source of thermal energy to produce roasted coffee. Sperandio et al. (2017) investigate two different solutions for recovering and valorizing spent grain from beer production: (1) conversion into pellet that can be used for heat generation in beer production and (2) production of biochar through the thermochemical process of pyro-gasification. Both studies show the technical and economic feasibility of these applications.

Several papers report the use of urban wastes as a replacement of coal in industrial processes. For instance, in Kawasaki (Japan) separated plastic and paper generated within the urban area are converted into high-performance solid fuel, which is then used in a steel plant as a substitute for coke and fuel in the blast furnace (Ohnishi et al. 2017). In Pingliang City (China), unsorted urban wastes are used to replace coal in a power plant (Dong et al. 2017).

From the environmental perspective, the adoption of such an approach can result in three main benefits: (1) reducing the amounts of wastes disposed of in landfills; (2) reducing the amounts of fossil fuels used in industrial processes; and (3) reducing the amounts of associated greenhouse gases (GHG) emitted in the atmosphere. In particular, savings in GHG emissions are due to avoided fuel production, transport, and combustion, as well as avoided disposal of wastes.[2] Considering the potential environmental benefits, the adoption of such an approach has been planned in Guiyang (China) (Dong et al. 2016; Li et al.

[2] One more source of saving in GHG emissions could be related to the fact that the process of burning wastes could produce a lower amount of CO_2 than the process of burning fossil fuels, *ceteris paribus*. However, in this regard, two issues should be highlighted. First, the reviewed literature has devoted a scant attention to investigate this aspect. Second, results can be highly case-specific, since they could depend on the characteristics of the waste and the fuel replaced, as well as on process parameters.

2015b), where two synergies can be developed: (1) 10 t/year of waste plastic can be used to replace 12 t of coal by cement, iron and steel plants, reducing CO_2 emissions by 31.2 kt/year; and (2) 100 t/year of coal gangue produced by coal industry can be reused by local power plants for electricity generation, saving fossil fuel by 30 ktce/year and reducing CO_2 emission by 78 kt/year. However, savings in CO_2 emissions are highly case-specific. In fact, Eckelman and Chertow (2013) highlight that burning wastes could produce more CO_2 than burning traditional fuels, *ceteris paribus*. This may depend on several technical issues, such as the replacement capability of wastes (i.e., how many units of wastes are required to replace one unit of fuel) and the CO_2 emission coefficients of both waste and the replaced fuel. For instance, for each ton of paper used in Kawasaki, CO_2 emissions can be reduced by 4.86 t, while 3.16 t of CO_2 can be saved per each ton of plastic used as fuel, *ceteris paribus* (Ohnishi et al. 2017).

3.3 Bioenergy production

Bioenergy production-based IS synergies can be classified according to business and geographic dimensions. From the business perspective, bioenergy production synergies can be implemented within one company, when the waste producer implements bioenergy production processes, or among different companies, so that a bioenergy production chain is developed. From the geographic perspective, the waste exploited for bioenergy production can be produced in rural, industrial, and urban areas.

Concerning the wastes produced in rural areas, Alfaro and Miller (2014) identify several energy-based IS synergies that can be adopted inside smallholder farms, aimed at producing electricity and biogas for internal use, and discuss their economic implications for farms. Sharib and Halog (2017) highlight the possible use of rubber wood as a biomass feedstock for electricity production. Zabaniotou et al. (2015) and Ruggieri et al. (2016) discuss how to produce energy from wastes generated by olive oil production. Pierie et al. (2017) and Yazan et al. (2018) analyze the electric energy production chain from animal manure in the Netherlands, where different manure producers can cooperate with one or more energy producers. In particular, Pierie et al. (2017) assess the possible economic and environmental benefits for the involved companies and the collectivity, respectively. Yazan et al. (2018) focus on the cooperation pathways among manure producers and bioenergy producers, investigating the manure exchange price that would enhance the willingness to cooperate of these actors. Several papers analyze palm-based energy production (e.g., empty fruit bunches, palm kernel shells, palm mesocarp fiber, palm oil mill effluent) in Malaysia. In particular, Ng et al. (2014b) and Ng et al. (2014a) propose a disjunctive fuzzy optimization approach to determine the configuration of production chain which optimizes the total economic performance, while Tan et al. (2016) and Andiappan et al. (2016) focus on exploring the fair allocation of economic benefits among all the actors based on their respective contributions toward the chain. In particular, Tan et al. (2016) propose a linear programming cooperative game model, while Andiappan et al. (2016) propose an optimization-based negotiation framework. Tan et al. (2016) also address the energy production chain from waste biomass of sago palm waste (e.g., sago fibers and sago bark), which is generated in sago starch food production typically to be found in tropical lowland forest in South East Asia countries and Papua New Guinea. Gonela and Zhang (2014) and Gonela et al. (2015) develop optimization models for designing the bioethanol production chain based on the IS approach, aimed at determining the configuration of the chain that maximizes the overall economic performance. Furthermore, Martin and Eklund (2011) suggest the opportunity to reuse the waste heat from ethanol production in biogas and biodiesel processing, as these processes can utilize low-temperature heat. Tsvetkova et al. (2015) investigate the biogas production chain using agricultural wastes, highlighting the key actors and modeling both material and monetary flows among them.

Concerning the wastes produced in urban areas, several papers explore the energy production from organic wastes, which on average account for around 46% of total municipal wastes (The World Bank 2012). Such a practice is considered as a useful strategy for mitigating the environmental impact created within urban areas. Apart from the energy producer, these IS synergies involve also citizens, responsible for waste production, and the local government, responsible for waste collection and disposal. Within urban areas, three kinds of organic wastes can be used to produce energy: food waste, waste cooking oil, and green wastes (i.e., wastes produced in green areas) (Fraccascia et al. 2016; Li et al. 2017). These wastes stem from household consumption, food retail (e.g., food selling in supermarkets), food service (e.g., food cooked and served in restaurants and canteens), and green areas maintenance (Albino et al. 2015). Furthermore, these organic wastes can be used in combination with wastes produced in rural areas. In this regard, Vega-Quezada et al. (2017) assess the technical and economic feasibility of producing biogas through a mixture of municipal urban waste and livestock manure. Nevertheless, the sludge resulting from wastewater treatment plants can be used to produce electric energy through cogeneration (e.g., Gonela and Zhang 2014; Yu et al. 2015a).

Concerning the use of industrial wastes for energy production, Sgarbossa and Russo (2017) and Santagata et al. (2017) investigate IS synergies implemented by companies belonging to the supply chain of meat products, where large amounts of slaughterhouse waste are produced. These wastes mainly consist of the portion of a slaughtered animal that cannot be sold as meat or used in meat products. All the unusable parts of the slaughtered carcass can be collected for processing from abattoirs, butchers, and food processing sites. Then, after a pretreatment process, the solid fraction (i.e., bone and meat) can be used in a cogeneration plant to produce energy. Velenturf (2016) highlights the exploitation of waste oils generated by fuel production to produce energy. Electric energy and biogas can also be produced from sludge generated by waste treatment processes (Benjamin et al. 2015; Li et al. 2015c; Maaß and Grundmann 2016; Sharib and Halog 2017; Tan et al. 2016; Tsvetkova et al. 2015; Yu et al. 2015a; Zijp et al. 2017).

In general, bioenergy production might create three environmental benefits: (1) a lower amount of (bio-) waste disposed of in landfills; (2) a lower amount of energy produced from conventional sources; and (3) a reduction in GHG emissions. In particular, the lower amount of GHG emissions results from the reduced amount of energy production from conventional sources and the (potential) reduced GHG emitted by the bioenergy production process.

4 Energy-based industrial symbiosis: drivers, barriers, and enablers

A variety of drivers, barriers, and enablers (DBEs) for the energy-based IS practice is found in the literature. Following Li et al. (2015c), we observe four different forms of DBEs: (1) *financial*, (2) *technological*, (3) *regulatory*, and (4) *institutional*. In general, *financial* DBEs refer to the monetary benefits and investments related to IS synergies. *Technological* DBEs concern any technical condition that influences the implementation of IS synergies. *Regulatory* DBEs are about any form of binding or encouraging legislation that is either in place or required to be established with respect to IS. Finally, *institutional* DBEs concern issues related to the organizational structure of involved firms, their business models, and their strategic behavior in implementing IS. Note that such a general classification is mainly based on the primary nature of DBEs—and not all their potential consequences or available solution concepts to deal with them. We use this categorization on various forms of DBEs in order to have a clear view of the essence of DBEs and their potential conflicting/enhancing interactions (see the upcoming subsections for detailed discussions).

While the above-mentioned four classes of DBE are common among the four categories, their manifestation is not necessarily the same. In the following subsections, we survey different forms of DBEs in the three energy-based IS categories presented in Sect. 3. Exploring the DBEs—categorized with respect to the type of energy-based symbiotic practice—might support firm managers' decisions during the process of IS evaluation as well as implementation. For instance, even if a manager encounters a barrier against a specific IS synergy, he/she may accept to explore the opportunity to implement IS—and not to evaluate it as an unpromising IS immediately—as he/she would be aware of potential enablers to overcome the barrier in question. In this way, the potential economic and socio-environmental benefits of the practice would not be dismissed.

Table 1 shows a summarized list of drivers, barriers, and enablers for each category, which are discussed in the following subsections.[3] Note that although some DBEs are common among different forms of energy-based IS practices, this table is generated merely based on specified DBEs in case studies included in the literature review.

4.1 DBEs in energy cascade IS

From the business perspective, in energy cascade cases the producer company usually sells the waste energy to the user company. Hence, waste energy producers are encouraged to implement IS synergies thanks to the additional revenues from selling waste energy, while waste users are willing to reduce energy costs, because of the lower energy price paid (Dong et al. 2014; Park and Park 2014). However, the willingness of companies to cooperate in energy cascade synergies might be hampered by the need to adjust their business strategy according to the IS practice (Wang et al. 2017a, b). This shows a trade-off between (former) *financial* drivers against (latter) *institutional* barriers in energy cascade IS practices. In addition, a fundamental prerequisite for the development of energy cascade is the capability to transport energy among different companies (Yune et al. 2016). Such a *technological* barrier limits the geographic scale of possible synergies, since the involved companies need to be located in close proximity so that energy transportation is technically and economically feasible.

From the technical perspective, energy users might have technical requirements (e.g., temperature and pressure of waste steam) for using the waste energy. Such requirements may make the IS synergy unfeasible—unless the waste energy user company implements technical changes in the production processes, which induce additional costs. Hence, a technological barrier may call for financial investments. Thus, in case the total foreseeable benefit (of implementing the IS practice) does not pay off such an investment, firms assess the practice as economically unpromising due to a *financial* barrier—which stems from a

[3] The four different forms of DBEs proposed by Li et al. (2015c) are not highlighted in this table because of a space limitation but are discussed in the following subsections.

Table 1 Drivers, barriers, and enablers for each energy-based category

Category	Drivers	Barriers	Enablers
Energy cascade	Additional revenues from selling energy (waste energy producer) Reducing energy costs (waste energy user)	Geographic distance among companies Need to adjust business model for energy sources (waste energy user) Building and managing infrastructures Need to implement technical changes in production processes Uncertainty in the amount of produced waste energy	Economic incentives from the government Regulations
Fuel replacement	Reducing waste disposal costs (waste energy producer) Reducing fuel purchase costs (waste energy user)	Uncertainty in waste production Need to implement technical changes in production processes Regulations on waste-fuel mix	Economic incentives from the government Regulations Technical support from the government
Bioenergy production	Reducing waste disposal costs Additional revenues from selling energy	Bioenergy production chains made by different actors with different interests Economic feasibility affected by several factors Access to bioenergy production technologies	Economic incentives from the government Regulations

technological origin. In principle, the return on investments—to implement energy cascade IS—mainly depends on the energy market price, as well as on the operational costs of IS that companies need to sustain (Wang et al. 2017a, b).

Furthermore, energy cascade IS synergies might face risks related to the fluctuations in the stream of waste energy supply or in the continuity of the energy demand—which can be affected by the seasonality of the main product demands, technical failures, or changing market dynamics (*technological/institutional* DBEs). As discussed by Albino et al. (2016), the uncertainty in waste production is also a typical problem for material-based IS synergies. In that case, to reduce the vulnerability of IS relations caused by the mismatch between demand and supply of waste companies can stock waste materials (when the amount of waste required is lower than the amount produced) and use them when the demand becomes higher than supply (Fraccascia et al. 2017b). However, this solution is not always applicable in the energy cascade synergies, mainly because energy storage technologies may not be economically sustainable (Andrews and Pearce 2011; Kikuchi et al. 2016). In such a case, the IS synergy has a low resilience to perturbations caused by the mismatch between demand and supply of waste energy (Wang et al. 2017a, b).[4]

The implementation of energy cascade may be in conflict with regulations that consider the linear economy as the established paradigm (Li and Ma 2015; Yu et al. 2015c). Yu et al. (2015c) classify the IS-related policies into three categories: (1) resource comprehensive utilization policies; (2) tax preference policies; and (3) CE and IS promotion policies (*regulatory* DBE). While the traditional set of policies merely focuses on fostering the industries to realize a desirable outcome from the economic, environmental, and social perspective, the CE-oriented legislations also take into account the methods that industries employ (e.g., exploiting IS practices). Hence, governments are ought to reduce the complexity and remove the barriers in implementing IS synergies through similar forms of legislative reform and creations—as illustrated in Yu et al. (2015b). For instance, by adopting regulations that specify boundaries on energy consumption and greenhouse gas (GHG) emissions, as well as policies aimed at nudging firms to discard obsolete processes and equipment, governments may enforce companies to implement energy cascade synergies (Cerceau et al. 2014; Lehtoranta et al. 2011; Lenhart et al. 2015; Wu et al. 2016b; Yu et al. 2015a). In parallel, governments might stimulate the application of advanced cleaner technologies through the provision of fiscal subsidies (Li et al. 2017; Wen et al. 2018) or directly supporting IS synergies by financing physical infrastructures required to exchange energy (Hein et al. 2017; Park and Park 2014). Although it is generally recognized that policy is an important instrument that can stimulate and remove barriers for IS, the number of regulations specifically aimed toward fostering IS or regulation in which IS appears as a promoted business model is still relatively low (Lehtoranta et al. 2011).

4.2 DBEs in fuel replacement IS

From the business perspective, companies are willing to adopt the fuel replacement approach aimed at reducing traditional fuel purchase costs (waste users) and waste disposal costs (waste producers)—*financial* DBEs. However, according to the European Waste

[4] For a detailed discussion on the resilience of IS synergies and its importance for the IS approach, we refer the readers to the following papers: (Ashton et al. 2017; Benjamin et al. 2015; Chopra and Khanna 2014; Fraccascia 2017a; Li and Shi 2015; Meerow and Newell 2015; Zeng et al. 2013; Zhu and Ruth 2013).

Hierarchy (European Parliament 2008), the use of waste materials as alternative fuel is suggested only in the case of low-quality wastes (e.g., wastes with a high percentage of impurities), because high-quality wastes might be used to replace production inputs—*regulatory* DBEs.[5] For instance, high-grade lignin can be used to replace carbon fibers and high-quality plastic can be used to replace Phenol (Gabriel et al. 2017).

A key barrier for the development of fuel replacement IS synergies is the lack of useful and reliable information on the waste demand and supply (Guo et al. 2016)—*institutional* DBE. In fact, as a common property among IS-based practices, it may happen that demand (supply) for a given waste exists, but firms producing (requiring) that waste are not aware of such a demand (supply) (Aid et al. 2017; Chertow 2007; Golev et al. 2015; Sakr et al. 2011; Zhu and Cote 2004). However, even in case of full information availability, several issues may hamper the use of wastes as fuels.

First, the waste may require a pretreatment process before being used as fuel, e.g., aimed at removing impurities (Fraccascia et al. 2017a; Herczeg et al. 2018). In such a case, companies need to design and implement additional processes, which are not related to their core business (*institutional* DBE). For instance, using the spent coffee grounds as traditional fuel in coffee roasting plants requires appropriate drying and pallet-making machinery (Allesina et al. 2017)—*technological* DBE. Purchase costs of these machineries and associated operational costs (e.g., maintenance, workforce, inputs, and energy) erode the economic benefits that companies gain from the IS approach. Again, we observe how the required institutional change (in the business model) calls for technological updates and accordingly requires financial investments.

Second, the whole idea of replacing fuels with wastes might be influenced by technical and regulatory issues. From the technical perspective, the waste might have different characteristics from the replaced fuel, e.g., a lower heating value. In such a situation, the replacement is not a perfect match—with respect to quality—but a considerable alternative. In other words, some characteristics may constrain the substitution, e.g., when the available quality of waste is lower than the required quality (on the receiver side). One explanation is that waste is not produced upon demand but emerge as secondary outputs of main production activities (Yazan et al. 2016). This may simply result in a mismatch with respect to both quantity and quality. Then, a common solution is to use a mixture of traditional fuels with the waste-based fuel. It should be noticed that such a practice may require to calibrate the burning facilities, e.g., furnaces, according to the specific waste-fuel mix they receive, which results in additional operations for companies to undertake.

Third, when a waste material is substituting a traditional fuel, environmental protection technologies must be adopted as well (Subulan et al. 2015). Otherwise, the traditional technologies that are in place (e.g., to filter the emissions caused by the traditional fuel) may be insufficient when a company either replaces or mixes the fuel with a non-traditional waste material, e.g., exhausted tires—*technological* DBE.

Fourth, from the governance perspective, one main driver behind the use of wastes as fuel is to promote the reduction of raw material consumption and the GHG emissions. To

[5] A common definition of waste quality is lacking in the context of IS. In fact, according to Prosman and Wæhrens (2019, p. 113), "the context in which many industrial symbiosis practices unfold complicates defining waste quality and developing suitable incentives for waste quality (Yenipazarli 2019)." Generally, the concept of waste quality can be related to the similarity of the waste to the replaced input, in terms of physicochemical characteristics. The more similar the waste characteristics are to those of replaced input, the higher the waste quality will be, *ceteris paribus*. In this regard, a low-quality waste can be considered as a waste characterized by a high content of impurities.

encourage such a practice, governments at regional, national or even international level can play a key role by means of economic and regulatory instruments, as well as by providing companies with technical support. For instance, governments can introduce economic incentives for firms that replace traditional fuels and enforce penalties against GHG emitters (Fraccascia et al. 2017b; Liu et al. 2018; Ohnishi et al. 2017)—*regulatory* DBE. Rosa and Beloborodko (2015) acknowledge that the necessity to comply with European environmental regulations—concerning waste landfilling—has made Latvian industrial companies review their by-product management practice and that IS became a useful approach to comply with these regulations. In addition to promoting IS via legislative actions, policymakers can facilitate the availability of information for companies. In fact, they can promote public meetings among stakeholders in which information related to produced or required wastes is disseminated leading toward collaborative IS actions (Costa and Ferrão 2010). Furthermore, a regularly updated information-sharing platform can be developed in which firms upload their waste generation/requirement information and also find useful data from other companies (Fraccascia and Yazan 2018; Grant et al. 2010; van Capelleveen et al. 2018).

Overall, the above-mentioned issues and their representation in IS characterize a specific DBE profile that a particular IS practice is facing with. Such a profile, which consists of all four types of financial, regulatory, institutional, and technological DBEs, in some aspects hampers and in some other aspects fosters the implementation of the energy-based IS in question. In principle, the awareness of firms (and supporting entities such as governments) about these DBEs supports their decisions in the process of evaluating and implementing fuel replacement IS practices.

4.3 DBEs in bioenergy production IS

From the business perspective, companies are willing to adopt such an alternative form of energy production because they can benefit from lower waste disposal costs and additional revenues from selling the energy produced from (bio-) wastes (Maaß and Grundmann 2016)—*financial* DBEs.

From the technical perspective, the access to required technologies for bioenergy production is a key facilitator behind producing energy from wastes—*technological* DBEs. For instance, Tan et al. (2016) mention that the availability of a biomass-based refinery system is the main requisite for the establishment of symbiotic relations in palm oil eco-industrial parks in Malaysia, as such a system utilizes biomass feedstock to simultaneously produce heat, power, and cooling energy on-site. In an olive farm case, Zabaniotou et al. (2015) show that, in the presence of required machinery, the bio-oil obtained from pyrolysis can generate enough electricity to not only cover the energy requirements of the olive milling procedure but also to produce an electricity surplus. While having access to the proper technology enables large process industries to implement IS and produce energy, the lack of access to such technologies may be a barrier for small and medium-sized enterprises.

From the economic perspective, the feasibility of bioenergy production IS synergies is affected by technical, spatial, and economic factors that are highly case-specific. These factors include different forms of DBEs in general and specific factors such as biowaste transportation costs, electricity price (to see if a bioenergy production IS is beneficial), waste treatment processes (that are able to treat bioresources), and up-to-date bioenergy production facilities. In some cases, depending on the above-mentioned factors, bioenergy production IS synergies might have a negative cost–benefit ratio, thus requiring financial support from governments to be implemented (Velenturf 2016; Zhang et al. 2013b)—*regulatory* DBEs. In fact, apart from creating economic benefits for the involved companies and environmental benefits for the society, bioenergy production practices can also contribute to developing regional economic and substance cycles, boosting a local or regional economy, and enhancing its competitiveness (Brent et al. 2012; Martin and Eklund 2011). Hence, regional and national governments may be interested in supporting the implementation of this approach by introducing monetary incentives (Vega-Quezada et al. 2017) or regulations that focus on enhancing energy efficiency or limiting renewable fuel usage and GHG emissions (Gonela et al. 2015). While in one hand some regulations (e.g., monetary incentives) should be established to foster bioenergy production IS practice, some binding regulations have to be removed—or updated.[6]

5 Discussion

The findings of the systematic literature review can be evaluated from various perspectives. We discuss the identified key DBE's for energy-based IS, the three primary stakeholders with respect to required actions involved for improving energy-based IS, and the role of structure, geography, and investments in energy-based IS.

The first set of findings address the identified key drivers, barriers, and enablers for energy-based IS (see Table 1). There appear to be differences in regard to the identified primary DBE's for each energy-based IS category: energy cascade, fuel replacement, and bioenergy production. While in general enablers appear to be fairly similar, i.e., all categories list economic incentives and regulations as enablers, drivers and barriers are more divergent among the categories. Unsurprisingly, it is the overall dominating presence of economic drivers in all categories, either resulting from cost savings or from revenues obtained through energy transactions. Many researchers (e.g., Chae et al. 2010; Costa and Ferrão 2010; Shi et al. 2010) argue that IS is mostly not the core business of organizations. Therefore, explained well by Ashton (2011), many industries lack the incentive to initiate IS, as they are more focused on their own economic interests and are unaware or disregard the common potential in forming partnerships. While some of these DBE's are likely to strengthen in forthcoming years (e.g., additional revenues from selling energy), others (e.g., adjusting business models and co-locating particular industries) are expected to change due to the current prospect of increasing the financial quantification of environmental pollution and material use. This is primarily due to the increased intrinsic value of energy caused by energy scarcity and the growing demand of energy triggered by the increasing population and the associated growing demand in rising economies.

Throughout the literature review, we came across three main types of actors that have a capacity to influence the formation of IS cooperation, being: governments (or institutional anchors), industries, and facilitating bodies. Typically, the role of industries is finding inputs that can be replaced by waste and vice versa, finding potential symbiotic partners, and assessing the relationship. The key role of the governments is to create environmental regulations, provide industries with economic incentives, and create public institutions aimed at supporting industries in adopting IS. Finally, facilitators play an anchor role by providing guidance on waste treatment, political support, technical and economic feasibility, and sometimes act as a governing organization facilitating infrastructure and monitoring shared facilities.

The success of energy-based IS is dependent on all three actors. As the literature shows, many IS relations benefit from the use of the results listed capabilities and instruments of these

[6] For instance, Yazan et al. (2018) show that the presence of some (IS-binding) regulations might negatively affect the economic performance of companies. Hence, policymakers should carefully select the appropriate "sweet spot" policy that balances economic and environmental performance.

actors. The primary factor in energy cascades is the economic viability, which is highly influenced by the fluctuating market price and forces companies to change business strategy accordingly in order to adopt IS (Wang et al. 2017a, b). This could be changed by creating more stable and higher energy prices. For fuel replacement, it is argued that waste should only be treated as fuel in the case of low-quality waste. Furthermore, the supply of waste should be stable. Institutional actors can provide a mix of regulations targeted to prevent high-quality waste from being burned, while low-quality waste to be a considerable option. Secondly, contracted stocking waste at centralized warehouses may create a more stable flow of waste that can enable a sustainable business model for new IS relations. Finally, bioenergy production is heavily influenced by the technological infrastructure required for production. Again, measures like financial support both for acquiring infrastructure as well as operating the bioenergy production can support the feasibility of bioenergy (Velenturf 2016). In addition, regulations, that foster bioenergy production and enhance energy efficiency of biofuel, are advised (Gonela et al. 2015).

From the cases analyzed, it is observed that energy-based IS takes different forms with respect to the involvement of companies and physical flows of heat and energy sources. One of the common cases is that a central energy company—mostly in the form of combined heat and power (CHP)—sends excess heat to a number of receivers operating in process industry. Similarly, a central firm operating in process industry sends the excess heat deriving from its production process to other companies operating in process industry. For both cases, also the urban use of excess heat is possible. To render such a business model applicable, pipeline systems must be established, which require considerable investments. How such investment costs should be shared among involved stakeholders is an essential practical issue. Investments can be allocated to involved companies as well as being partially shared by an anchor company that generates or receives the most part of excess heat. The involvement of governments in investment-sharing is also possible via financing pipeline establishment. In such cases, technical issues such as the use of excess heat in the final destination should be carefully addressed. For example, the calorific value of the excess heat sent to a company operating in process industry and to households might be different, calling for adjustments in pipeline systems. There might also be differences between companies operating in disengaged process industries in terms of energy use. While a CHP intuitively would have economic gains thanks to additional sales of heat, for an anchor company operating in the process industry the economic gains are mostly in the form of cost reduction.

In terms of physical flows, involved companies might have different roles in the symbiosis: a company might provide energy source but do not receive energy, provide energy source and receive energy, do not provide energy source but receives energy. When multiple actors are involved, physical flows among companies might be one-to-one, multiple-to-one, or one-to-multiple. In addition, some cases are based on the substitution of the energy source, while some cases involve direct energy production/use. Implementing such a framework of physical flows would assist companies to understand the (potential) typology of the symbiotic network and define the centrality degree of each involved actor. Such an approach might enlighten the question of investment-sharing revealing the operational, economic, and environmental importance of each company for the network.

From the geographical perspective, a number of case studies display successful cooperation between industry and urban areas. On the other hand, the use of organic resources for particularly bioenergy production is commonly observed in rural areas, while there are also cases from the use of food waste, cooking oil waste and food/beverage processing waste in urban areas. So, the potential of energy-based-IS exists for both urban and rural areas involving small-medium enterprises, large-scale companies, local/urban communities, and (local) governments. This shows a clear indication that best-practices occur when there is the involvement of multiple stakeholders.

In terms of the additional costs of material-based IS, transportation costs, waste treatment costs, and transaction costs are observed to be the most relevant ones. In the case of energy-based industrial symbiosis, investment costs appear as the most relevant additional costs. This is a challenge to neutralize the savings associated with waste emission costs and traditional resource purchase costs. Therefore, future practices might show economic trade-off challenges, calling for the attention of governments in terms of subsidies or incentives, in line with their sustainable development agendas.

From the analysis of results, it can be highlighted that the environmental and economic benefits created by energy-based IS synergies are strongly case dependent. In particular, the environmental benefits depend on several factors, such as how much energy can be saved via IS, the CO_2 production rate of that energy source, how much energy can be produced via IS, the CO_2 production rate of the energy produced via IS, etc. Also the economic benefits depend on several factors, different than those above-mentioned, such as the additional costs required to implement and operate the energy-based IS synergies. Therefore, both the economic and the environmental feasibility of each energy-based IS synergy should be carefully investigated a priori. In this regard, future research should address several issues. From the environmental perspective, the environmental (current and potential) benefits from energy-based IS should be investigated more in-depth, for instance via methodologies based on thermodynamics—e.g., emergy analysis (e.g., Ren et al. 2016) and exergy analysis (e.g., Valero et al. 2013)—or LCA (e.g., Aissani et al. 2019; Martin 2019). In this regard, there is an extensive literature on the adoption of the above-mentioned methodologies specifically to analyze IS (Fraccascia and Giannoccaro 2020), but few contributions concern energy-based IS synergies. Furthermore, the process of using wastes instead of fossil fuels should be investigated more in depth, in order to highlight whether, *ceteris paribus*, using wastes would result in additional GHG emissions compared to the emissions resulting from using fossil fuels (see, e.g., Eckelman and Chertow 2013). In fact, some cases reported by the literature show that the use of alternative fuels could have negative consequences from the environmental perspective (e.g., Man et al. 2016). Also this issue could be investigated via LCA analysis. In fact, in this literature analysis, only few out of 96 articles analyzed (e.g., Eckelman and Chertow 2013; Geng et al. 2010; Mattila et al. 2012; Pakarinen et al. 2010; Pierie et al. 2017; Sokka et al. 2011) adopt LCA to energy-based IS, while the rest of them, having different focuses, skip the use of the LCA, which is critically important to measure the holistic contribution of IS rather than the core contribution. From the economic perspective, the profitability of energy-based IS synergies should be investigated more in depth, taking into account the investment costs and economic accounting of environmental cost reductions, which might be a base for governments to decide for subsidy distribution among stakeholders. Accordingly, sustainable business implementation via fair cost- and benefit-sharing should also be researched. Impacts of energy-based IS implementation on the traditional supply chains of companies, particularly in terms of contracts and business strategy change between companies, is also an open field of research. Finally, cross-cutting operational dynamics of water-based, material-based, service-based, and energy-based IS can be searched and a general framework for operations of IS can be implemented.

Finally, the authors would like to recognize a potential limitation of this paper. In fact, some articles could address cases of symbiotic synergies without directly defining them as IS (e.g., Man et al. 2018, 2020). These papers are not collected by the bibliographic research, which is designed to take into account the definition of IS (see Sect. 2). However, this limitation does not affect the main results of this research.

6 Conclusion

This paper addresses the different types of implementations of IS linked to one of our society's current and future concerns, i.e., energy security. Companies' traditional linear approach to producing and selling more goods (independently from society's demand) triggers a substantial increase in energy consumption in the production phase of goods. Furthermore, society's unsustainable consumption pattern, which is also highly energy-intensive, increases our hunger for energy sources to run the modern world economy and put the energy security in high ranks in future agendas of governments.

From the literature survey conducted, it is concluded that energy-based IS is one of the pioneering fields to achieve energy transition from linear to circular economy.[7] The field achieved an encouraging but not a sufficient number of success stories and barriers are still high and it starves for finding answers to a wide range of questions. The DBE analysis points out that the efforts to demolish financial, regulatory, technological, and institutional barriers have been insufficient up-to-date.

The following topics are the future research problems associated with multiple (potential) stakeholders in the IS-based.

How to reduce investment-related financial barriers? Existing excess heat transfer pipelines are constructed for short distances and the involvement of long-distance companies to such pipeline systems faces the financial barrier. Indeed, it is already expensive to construct an excess heat transfer pipeline between two companies. So, there is more way to go to understand how an excess heat transfer network would be implemented by reducing investment costs. Reduction in investment costs can be associated with multiple factors such as the use of alternative materials or production techniques for the construction of pipelines. Sustainable finance would also play a critical role to tackle with high investment costs in terms of moderate pay-back options which allows investors to internalize the environmental and social externalities. Internalization of environmental and social externalities require strong engagement and encouragement of (local) governments to safeguard the needs of the society and the environment while facilitating the economic viability of such big projects. In short, multiple stakeholder engagement is a must.

How to achieve 'coupled management of IS' at operational level? This is critical to reduce operational costs and a challenge due to the dynamic physical conditions of excess energy and the dynamic market conditions for the principal products of involved companies. Some cases might require improvement of physical or technical conditions for technical reasons, while some cases might require temporary energy storage to tackle with supply–demand mismatch fluctuations. Hence, a cooperation between thermodynamics, purchasing management and operations management research fields would contribute to decrease financial and logistical barriers giving an impetus on dynamic purchasing and pricing of transferred energy. Collaborative demand forecasting to reduce supply–demand mismatch, dynamic contracts to achieve fairness in cost- and benefit-sharing, and multi-lateral contracts to achieve stable and sustainable energy cascades are critical. If barriers can be demolished, then the industry's dependency on fossil fuels (particularly natural gas) can significantly decrease.

How to achieve society's integration? The first answer to this question is 'via integrating energy industry-household energy systems'. If economic viability can be demonstrated, the

[7] Although this paper is focused on energy-based IS, the authors recognize that there are also other strategies to achieve energy transition from linear to circular economy. In fact, green energies , e.g., photovoltaic energy (e.g., D'Adamo 2018) and wind energy (e.g., Hao et al. 2020), can play an important role toward the energy transition to circular economy.

excess heat transfer pipelines can reach households. This might be quite promising for households living in industrial areas that produce a sufficient supply of excess heat. The impact would be: (1) society respires cleaner air due to the fossil energy source reduction in the industrial zone and household areas; (2) society has the chance of reducing its energy bills (which might require governmental support); and (3) the society, governments, and the industry would achieve the integral circular economy. Consumer organizations would play a glue role in this integration.

Not only energy loops to be closed: what about closing other loops in cooperation with other sectors? Closing the energy loop via energy cascades, fuel replacement, and bioenergy production is only a part of the energy-based IS. However, there are side stream wastes that offer new business and loop-closing opportunities, which are likely to enhance the economic viability of energy-based IS. For example, integrated recovery of value-added materials from manure (via biorefining) would also economically facilitate the viability of biogas production. Furthermore, it would significantly reduce the economic burdens for animal farmers who need to pay manure discharge or treatment costs. As a result, the increase in meat and dairy product prices can be ceased, increasing the social sustainability in terms of access to food. So, circularity is complementary: once you start to close loops the others will follow, as long as multiple stakeholder engagement is ensured and individual needs are taken into account in an integrated manner.

What about the role of (local) governments? Governments might support the diffusion of energy-based IS networks via a thorough understanding of the entire life cycle impact of taken actions. Inter-sectorial activities like IS take place in long and complex supply chains and influence upstream and downstream actors as well as the environment and society. Industrial ecosystems transform and evolve in a circular manner that requires behavioral and strategic changes both in the society and in industry. The (local) governments play a key role to encourage companies through IS implementation via providing subsidies or applying binding regulations. Similarly, the sustainable energy consumption can be promoted via incentives to households who take place in energy cascades via using excess heat or bio-based energy. The position of traditional energy suppliers might produce conflicts of interest among multiple actors which requires also a transition plan from governments so to achieve resilient circular transformation.

In conclusion, an enormous field is open for researchers to conduct multi/cross/inter-disciplinary research on the above-mentioned niches to achieve the circular energy transition. The authors expect that energy-based IS will play a pioneering role to activate multiple industries for closing more loops in the future and quick establishment of the sustainable future of circular economy.

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Appendix

List of the papers considered in the literature review.

Title	Year	Journal	References	IS category			Waste produced in		
				Energy cascade	Fuel replacement	Bioenergy production	Industrial area	Urban area	Rural area
Combining a Geographical Information System and Process Engineering to Design an Agricultural-Industrial Ecosystem	2001	Journal of Industrial Ecology	Özyurt and Realff (2001)			■			■
Applying industrial ecology in rapidly industrializing Asian countries	2004	International Journal of Sustainable Development	Geng and Cote (2004)		■		■		
Emergy evaluation of Eco-Industrial Park with Power Plant	2005	Ecological Modelling	Wang et al. (2005)	■			■		
Emergy evaluation of combined heat and power plant eco-industrial park	2006	Resources, Conservation and Recycling	Wang et al. (2006)	■			■		
Industrial Symbiosis in Kalundborg, Denmark	2006	Journal of Industrial Ecology	Jacobsen (2006)	■			■		
Developing Integration in a Local Industrial Ecosystem – an Explorative Approach	2007	Business Strategy and the Environment	Wolf et al. (2007)	■			■		
Industrial Symbiosis in the Kwinana Industrial Area (Western Australia)	2007	Measurement and Control	Harris (2007)	■			■		
The benefits of a Brazilian agro-industrial symbiosis system and the strategies to make it happen	2007	Journal of Cleaner Production	Ometto et al. (2007)			■			■
A case study of industrial symbiosis: Nanning Sugar Co., Ltd. in China	2008	Resources, Conservation and Recycling	Yang and Feng (2008)		■		■		
Model-Centered Approach to Early Planning and Design of an Eco-Industrial Park around an Oil Refinery	2008	Environmental Science Technologies	Zhang et al. (2008)	■			■		
Using an optimization model to evaluate the economic benefits of industrial symbiosis in the forest industry	2008	Journal of Cleaner Production	Karlsson and Wolf (2008)		■				■
Comparative analysis of socio-economic and environmental performances for Chinese EIPs: case studies in Baotou, Suzhou, and Shanghai	2009	Sustainability Science	Zhang et al. (2009)	■			■		
A case study of industrial symbiosis development using a middle-out approach	2010	Journal of Cleaner Production	Costa and Ferrão (2010)		■		■		
Developing country experience with eco-industrial parks a case study of the Tianjin Economic-Technological Development Area in China	2010	Journal of Cleaner Production	Shi et al. (2010)	■	■		■	■	
Energy conservation and circular economy in China's process industries	2010	Energy	Li et al. (2010)	■			■		
Evaluation of innovative municipal solid waste management through urban symbiosis: a case study of Kawasaki	2010	Journal of Cleaner Production	Geng et al. (2010)	■				■	
Industrial Recycling Networks as Starting Points for Broader Sustainability-Oriented Cooperation?	2010	Journal of Industrial Ecology	Posch (2010)	■			■		
Optimization of a waste heat utilization network in an eco-industrial park	2010	Applied Energy	Chae et al. (2010)	■			■		
Sustainability and industrial symbiosis—The evolution of a Finnish forest industry complex	2010	Resources, Conservation and Recycling	Pakarinen et al. (2010)	■		■	■		

Analyzing the Environmental Benefits of Industrial Symbiosis: Life Cycle Assessment Applied to a Finnish Forest Industry Complex	2011	Journal of Industrial Ecology	Sokka et al. (2011)		■		■		
Environmental and economic assessment of a greenhouse waste heat exchange	2011	Journal of Cleaner Production	Andrews and Pearce (2011)	■					■
Improving the environmental performance of biofuels with industrial symbiosis	2011	Biomass and Energy	Martin and Eklund (2011)	■		■	■		■
Managing Performance Expectations of Industrial Symbiosis	2011	Business Strategy and the Environment	Ashton (2011)	■		■	■		
Planning and Uncovering Industrial Symbiosis: Comparing the Rotterdam and Östergötland regions	2011	Business Strategy and the Environment	Baas (2011)	■	■		■		
Industrial symbiosis and the policy instruments of sustainable consumption and production	2011	Journal of Cleaner Production	Lehtoranta et al. (2011)	■			■		
Enabling industrial symbiosis by a facilities management optimization approach	2012	Journal of Cleaner Production	Meneghetti and Nardin (2012)		■		■		
Methodological Aspects of Applying Life Cycle Assessment to Industrial Symbioses	2012	Journal of Industrial Ecology	Mattila et al. (2012)	■	■		■		
Mineral Carbonation as the Core of an Industrial Symbiosis for Energy-Intensive Minerals Conversion	2012	Journal of Industrial Ecology	Brent et al. (2012)	■	■		■		
Analysis of low-carbon industrial symbiosis technology for carbon mitigation in a Chinese iron/steel industrial park: a case study with carbon flow analysis	2013	Energy Policy	Zhang et al. (2013b)		■		■		
Environmental and economic gains of industrial symbiosis for Chinese iron/steel industry: Kawasaki's experience and practice in Liuzhou and Jinan	2013	Journal of Cleaner Production	Dong et al. (2013b)	■			■		
Investigation of the residual heat recovery and carbon emission mitigation potential in a Chinese steelmaking plant: A hybrid material/energy flow analysis case study	2013	Sustainable Energy Technologies and Assessments	Zhang et al. 2013a)		■		■		
Life cycle energy and environmental benefits of a US industrial symbiosis	2013	The International Journal of Life Cycle Assessment	Eckelman and Chertow (2013)	■	■		■		
Promoting low-carbon city through industrial symbiosis: A case in China by applying HPIMO model	2013	Energy Policy	Dong et al. 2013a)	■			■		
Applying Industrial Symbiosis to Smallholder Farms: Modeling a Case Study in Liberia, West Africa	2014	Journal of Industrial Ecology	Alfaro and Miller (2014)			■			■
Design of the optimal industrial symbiosis system to improve bioethanol production	2014	Journal of Cleaner Production	Gonela and Zhang (2014)			■			■
Multi-objective Design of Industrial Symbiosis in Palm Oil Industry	2014	Computer Aided Chemical Engineering	Ng et al. (2014a)			■			■
Disjunctive fuzzy optimisation for planning and synthesis of bioenergy-based industrial symbiosis system	2014	Journal of Environmental Chemical Engineering	Ng et al. (2014b)			■			■

Emergy-based assessment on industrial symbiosis: a case of Shenyang Economic and Technological Development Zone	2014	Environmental Science and Pollution Research	Geng et al. (2014)	■			■		
From Refining Sugar to Growing Tomatoes: Industrial Ecology and Business Model Evolution	2014	Journal of Industrial Ecology	Short et al. (2014)	■					■
Implementing industrial ecology in port cities: International overview of case studies and cross-case analysis	2014	Journal of Cleaner Production	Cerceau et al. (2014)	■				■	
Securing a Competitive Advantage through Industrial Symbiosis Development	2014	Journal of Industrial Ecology	J. Y. Park and Park (2014)	■			■		
Uncovering opportunity of low-carbon city promotion with industrial system innovation Case study on industrial symbiosis projects in China	2014	Energy Policy	Dong et al. (2014)	■			■	■	
Methods for assessing the energy-saving efficiency of industrial symbiosis in industrial parks	2015	Environmental Science and Pollution Research	Li et al. (2015a)	■			■		
A decision support method for development of industrial synergies: Case studies of Latvian brewery and wood-processing industries	2015	Journal of Cleaner Production	Rosa and Beloborodko (2015)		■		■		■
Analyzing the disruption resilience of bioenergy parks using dynamic inoperability input–output modeling	2015	Environment Systems and Decisions	(Benjamin et al. 2015)		■	■	■		
Boosting circular economy and closing the loop in agriculture: Case study of a small-scale pyrolysis–biochar based system integrated in an olive farm in symbiosis with an olive mill	2015	Environmental Development	(Zabaniotou et al. 2015)			■			■
Building green supply chains in eco-industrial parks towards a green economy: Barriers and strategies	2015	Journal of Environmental Management	Li et al. (2015c)	■			■		
Circular economy of a papermaking park in China: A case study	2015	Journal of Cleaner Production	Li and Ma (2015)	■			■		
Designing an environmentally conscious tire closed-loop supply chain network with multiple recovery options using interactive fuzzy goal programming	2015	Applied Mathematical Modelling	Subulan et al. (2015)		■		■		
Evolution of industrial symbiosis in an eco-industrial park in China	2015	Journal of Cleaner Production	Yu et al. (2015c)	■			■		
From an eco-industrial park towards an eco-city: A case study in Suzhou, China	2015	Journal of Cleaner Production	Yu et al. (2015a)	■				■	
Industrial symbiosis as a countermeasure for resource dependent city: A case study of Guiyang, China	2015	Journal of Cleaner Production	Li et al. (2015a)	■			■		
Industrial Symbiosis for a Sustainable City: Technical, Economical and Organizational Issues	2015	Procedia Engineering	Albino et al. (2015)			■		■	
New roles for local authorities in a time of climate change: The Rotterdam Energy Approach and Planning as a case of urban symbiosis	2015	Journal of Cleaner Production	Len hart et al. (2015)	■				■	
Quantifying CO2 emission reduction from industrial symbiosis in integrated steel mills in China	2015	Journal of Cleaner Production	Yu et al. (2015d)	■			■		
Reducing carbon emissions through industrial symbiosis: A case study of a large enterprise group in China	2015	Journal of Cleaner Production	Yu et al. (2015b)		■		■		
Replication of industrial ecosystems: The case of a sustainable biogas-for-traffic solution	2015	Journal of Cleaner Production	Tsvetkova et al. (2015)	■					■

Stochastic optimization of sustainable industrial symbiosis based hybrid generation bioethanol supply chains	2015	Computers and Industrial Engineering	Gonela et al. (2015)			■			■
The decline of eco-industrial development in Porto Marghera, Italy	2015	Journal of Cleaner Production	Mannino et al. (2015)	■			■		
The industrial symbiosis approach: A classification of business models	2015	Procedia Environmental Science, Engineering and Management	Albino and Fraccascia (2015)		■		■		
The Resilience of Interdependent Industrial Symbiosis Networks: A Case of Yixing Economic and Technological Development Zone	2015	Journal of Industrial Ecology	Li and Shi (2015)			■	■		
A meta-model of inter-organisational cooperation for the transition to a circular economy	2016	Sustainability	Ruggieri et al. (2016)		■				■
A novel methodology for the design of waste heat recovery network in eco-industrial park using techno-economic analysis and multi-objective optimization	2016	Applied Energy	Zhang et al. (2016)	■					
Added-value from linking the value chains of wastewater treatment, crop production and bioenergy production: A case study on reusing wastewater and sludge in crop production in Braunschweig (Germany)	2016	Resources, Conservation and Recycling	Maaß and Grundmann (2016)			■		■	
An optimization-based cooperative game approach for systematic allocation of costs and benefits in interplant process integration	2016	Chemical Engineering Research and Design	Tan et al. (2016)			■	■		
An optimization-based negotiation framework for energy systems in an eco-industrial park	2016	Journal of Cleaner Production	Andiappan et al. (2016)			■			■
Business models for industrial symbiosis: A guide for firms	2016	Procedia Environmental Science, Engineering and Management	Fraccascia et al. (2016)			■		■	
Design technologies for eco-industrial parks: From unit operations to processes, plants and industrial networks	2016	Applied Energy	Pan et al. (2016)			■			■
Evaluation of promoting industrial symbiosis in a chemical industrial park: A case of Midong	2016	Journal of Cleaner Production	Guo et al. (2016)		■		■		
Greening Chinese chemical industrial park by implementing industrial ecology strategies: A case study	2016	Resources, Conservation and Recycling	Yune et al. (2016)	■			■		
Industrial Symbiosis Centered on a Regional Cogeneration Power Plant Utilizing Available Local Resources: A Case Study of Tanegashima	2016	Journal of Industrial Ecology	Kikuchi et al. (2016)	■			■		
Insight into industrial symbiosis and carbon metabolism from the evolution of iron and steel industrial network	2016	Journal of Cleaner Production	Wu et al. (2016b)	■			■		
Promoting industrial symbiosis: empirical observations of low-carbon innovations in the Humber region, UK	2016	Journal of Cleaner Production	Velenturf (2016)			■			■
Towards preventative eco-industrial development: an industrial and urban symbiosis case in one typical industrial city in China	2016	Journal of Cleaner Production	Dong et al. (2016)	■	■		■	■	
A comprehensive evaluation on industrial urban symbiosis by combining MFA, carbon footprint and emergy methods—Case of Kawasaki, Japan	2017	Ecological Indicators	Ohnishi et al. (2017)		■			■	
A proactive model in sustainable food supply chain: Insight from a case study	2017	International Journal of Production Economics	Sgarbossa and Russo (2017)			■	■		

An environmental assessment of electricity production from slaughterhouse residues. Linking urban, industrial and waste management systems	2017	Applied Energy	Santagata et al. (2017)			■		■	
Carbon dioxide and heat integration of industrial parks	2017	Journal of Cleaner Production	Hassiba et al. (2017)	■			■		
Comparing the vulnerability of different coal industrial symbiosis networks under economic fluctuations	2017	Journal of Cleaner Production	Wang et al. (2017b)	■			■		
Early front-end innovation decisions for self-organized industrial symbiosis dynamics-A case study on lignin utilization	2017	Sustainability	Gabriel et al. (2017)		■		■		
Eco-benefits assessment on urban industrial symbiosis based on material flows analysis and emergy evaluation approach: A case of Liuzhou city, China	2017	Resources, Conservation and Recycling	Sun et al. (2017)	■				■	
Emergy analysis on industrial symbiosis of an industrial park – A case study of Hefei economic and technological development area	2017	Journal of Cleaner Production	Fan et al. (2017)	■			■		
Enhancing value chains by applying industrial symbiosis concept to the Rubber City in Kedah, Malaysia	2017	Journal of Cleaner Production	Sharib and Halog (2017)			■			■
Improving the Sustainability of Farming Practices through the Use of a Symbiotic Approach for Anaerobic Digestion and Digestate Processing	2017	Resources	Pierie et al. (2017)			■			■
Increasing the Value of Spent Grain from Craft Microbreweries for Energy Purposes	2017	Chemical Engineering Transactions	Sperandio et al. (2017)		■		■		
Integrated stability analysis of industrial symbiosis networks	2017	Chemical Engineering Transactions	Wang et al. (2017a)	■			■		
Low-carbon benefits of industrial symbiosis from a scope-3 perspective: a case study in China	2017	Applied Ecology and Environmental Research	Li et al. (2017)	■			■		
Method selection for sustainability assessments: The case of recovery of resources from waste water	2017	Journal of Environmental Management	Zijp et al. (2017)			■	■		
Performance indicators for a circular economy: A case study on post-industrial plastic waste	2017	Resources, Conservation and Recycling	Huysman et al. (2017)		■		■		
Spent coffee grounds as heat source for coffee roasting plants: Experimental validation and case study	2017	Applied Thermal Energy	Allesina et al. (2017)		■			■	
Stakeholder power in industrial symbioses: A stakeholder value network approach	2017	Journal of Cleaner Production	Hein et al. (2017)	■			■		
Synergies between agriculture and bioenergy in Latin American countries: A circular economy strategy for bioenergy production in Ecuador	2017	New Biotechnology	Vega-Quezada et al. (2017)			■			■
Technical efficiency measures of industrial symbiosis networks using enterprise input-output analysis	2017	International Journal of Production Economics	Fraccascia et al. (2017a)		■		■		
Approaches and policies for promoting industrial park recycling transformation (IPRT) in China: Practices and lessons	2018	Journal of Cleaner Production	Wen et al . (2018)	■			■		
Comparative study on the pathways of industrial parks towards sustainable development between China and Canada	2018	Resources, Conservation and Recycling	Liu et al. (2018)		■		■		
Cooperation in manure-based biogas production networks: An agent-based modeling approach	2018	Applied Energy	Yazan et al. (2018)		■	■			■

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