Renewable energy in eco-industrial parks and urban-industrial symbiosis: a literature review and a conceptual synthesis

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Abstract

Replacing fossil fuels with renewable energy sources is considered as an effective means to reduce carbon emissions at the industrial level and it is often supported by local authorities. However, individual firms still encounter technical and financial barriers that hinder the installation of renewables. The eco-industrial park approach aims to create synergies among firms thereby enabling them to share and efficiently use natural and economic resources. It also provides a suitable model to encourage the use of renewable energy sources in the industry sector. Synergies among eco-industrial parks and the adjacent urban areas can lead to the development of optimized energy production plants, so that the excess energy is available to cover some of the energy demands of nearby towns. This study thus provides an overview of the scientific literature on energy synergies within eco-industrial parks, which facilitate the uptake of renewable energy sources at the industrial level, potentially creating urban-industrial energy symbiosis. The literature analysis was conducted by arranging the energy-related content into thematic categories, aimed at exploring energy symbiosis options within eco-industrial parks. It focuses on the urban-industrial energy symbiosis solutions, in terms of design and optimization models, technologies used and organizational strategies. The study highlights four main pathways to implement energy synergies, and demonstrates viable solutions to improve renewable energy sources uptake at the industrial level. A number of research gaps are also identified, revealing that the energy symbiosis networks between industrial and urban areas integrating renewable energy systems, are under-investigated.

Keywords

Carbon emissions reduction; Renewable energy sources; Industrial symbiosis; Eco-industrial parks; Industrial energy symbiosis; Urban-industrial energy symbiosis

Highlights

- Options to reduce industry GHG emissions
- Review and analysis of energy symbiosis schemes including renewable energy sources
- Energy strategy within eco-industrial parks to promote the use of renewable energy sources
- Urban-industrial energy symbiosis including renewable energy sources

1. Introduction

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Reducing the negative environmental impacts of industries is a major challenge, both in advanced and emerging economies. The need for reducing atmospheric emissions, which are responsible for climate change, is all the more urgent in densely industrialized areas, which are traditionally located nearby highly populated zones, such as those in Europe [1]. The quality of air in rapidly growing economies is also worsening, as industrial clusters bring about both economic growth and environmental impacts [2]. Issues of environmental resource efficiency, sustainable processes and energy choices must be considered when promoting sustainable industrial development [3].

Global CO_2 emissions from the industry sector include energy-related emissions and CO_2 emissions from industrial processes. Direct emissions mainly originate from fuel combustion and industrial processes, while indirect emissions are primarily from energy production (electricity and heat) [4]. Therefore decarbonization processes should be based on the sustainable transformation of production processes and sustainable energy sources [5].

The Industrial Development Report 2018 of the United Nations Industrial Development Organization [6] reaffirms that industries should create a “virtuous circle of sustainable consumption is a system in which fossil fuel inputs are gradually replaced with renewable energy, materials and energy are used more efficiently, and final goods are reused or recycled to feed back into the input-generation process”.

Improvements in energy and material efficiency, and a greater deployment of renewable energy, are considered as essential for a low-carbon transition [7]. The potential for CO_2 emission reduction offered by renewable energy sources (RES) in energy production and industrial processes is emphasized by the International Energy Agency [8]. Industries can buy clean energy (e.g., hydropower) for processes or integrate renewable energy systems. Technological advancements now provide solutions for adopting intermittent RES through methods such as distributed energy generation [9] and smart grids [10]. The main renewable energy sources suitable for industrial application are biomass, solar radiation (thermal or photovoltaics), ground heat and wind. The maturity and cost reduction of renewables technology, in which renewable resources are abundant and the cost of energy produced by RES is getting closer to fossil fuel parity, makes RES a feasible alternative.

However, single firms, and particularly single small-medium enterprises (SMEs), are reluctant to invest in energy efficiency solutions and RES, mainly due to techno-economic factors [11]. Decision-making in energy projects requires expertise, which is often not internally available, and involves technical, economic, environmental and social issues that SMEs may find difficult to manage [12].

Supported supply chain initiatives have been demonstrated to be effective in improving energy efficiency, leading to greenhouse gas (GHG) emission reductions and cost savings both for suppliers and manufacturers [13]. Approaching sustainable solutions and energy planning from the district level can encourage the implementation of inter-firm projects that promote energy exchanges and collective production to reduce the use of fossil fuels. The sharing of the same geographical and administrative conditions (climate, energy stakeholders, local policies and networks) represents an opportunity to implement energy strategies aimed at rationalizing consumption and optimizing the systems of supply [14].

Eco-industrial parks (EIPs) are naturally suited to foster cooperation and resource-sharing among businesses. EIPs comprise a community of businesses located in the same geographical area, connected by collaborative [15] and competitive relationships [16]. EIPs can be considered an application of the industrial symbiosis (IS) approach to industrial systems. IS rests on building synergies among different firms to develop closed-loop systems through the physical exchange of resources (materials, by-products, water, energy), thus reducing pollution and the exploitation of natural resources. EIPs are modelled as networks of manufacturing and service businesses, which aim to share and efficiently use natural and economic resources, increase the economic performance of the participants, reduce the overall environmental impact and create benefits for local communities [17].

Thus, a collective effort to increase the use of RES is a viable method of reducing the carbon footprint of industry as cooperation among businesses enables knowledge gaps to be overcome and the investment, maintenance, and management costs of the energy infrastructure to be shared. The industrial sites can evolve into energy producers, able to satisfy internal energy demands and also to supply neighbouring populated areas with the excess energy [18], thus minimizing the environmental impact of electricity production [19]. Urban-industrial symbiosis (UIS) extends the concept of industrial symbiosis to urban-industrial synergies, and provides the opportunity of building up fruitful exchanges of resources and waste between cities and local EIPs, and reducing carbon emissions both at industrial park and urban levels [20].

Research into EIPs is well-established and the published literature provides a consolidated body of knowledge. Reviews of EIP studies [21–23] and of RES in industrial applications [24–26] have been presented. However, to the best of our knowledge no review integrates these issues or explores the possibilities of EIP and RES integration, which combine the industrial and the nearby urban levels. Thus, the aim of this study is to fill this research gap and investigate how EIP models can help promote the use of RES, at both industrial and urban levels.

This paper presents an overview of the scientific literature on energy synergies within EIPs that enable RES uptake at the industrial level. It provides a framework for the knowledge on energy sustainability in industrial parks and outlines the inter-firm cooperation schemes that can foster the adoption of emission-mitigating technologies. It demonstrates viable solutions and the effectiveness of RES integration within EIPs aimed at reducing the carbon footprint of industries, and potentially creating urban-industrial energy symbiosis. Finally, it suggests opportunities for future research.

The remainder of this article is structured as follows. Section 2 presents the research motivation and questions. Section 3 describes the literature search, including keywords used and the subsequent steps. Section 4 provides an analysis of the selected articles, arranged by thematic content. Section 5 includes a discussion of the findings and a conceptual synthesis highlighting the issues and possibilities for future research. Lastly, section 6 draws the conclusions.

2. Motivation and research questions

Many literature reviews of research into issues related to eco-industrial parks have been found, which analyse both academic areas of interest and the features of projects, as for example in [27]. The initial literature search was conducted using the Science Direct and Web of Science databases, combining the terms “industrial symbiosis”, “eco-industrial parks” and “energy” and selecting papers classified as “reviews”. Table 1 provides a summary of relevant recently published surveys or reviews (11 out of 25) on the topic. The table also reports the number of articles that each study reviewed, used for a backward search.

Focus	Keywords	N. of reviewed papers	Year	Source
Policy conceptualization to clarify the mechanisms of policy intervention and facilitation of industrial symbiosis.	Industrial symbiosis; Policy intervention; Policy translation; Circular economy; Eco-industrial park; China	37 out of 118 references	2014	[21]
Industrial ecology contribution to Circular economy	Circular Economy; Industrial Symbiosis; Industrial Ecology; Bibliometric analysis	43 out of 110 references	2018	[28]
Optimization methods for designing eco industrial parks	Eco-industrial parks; Industrial ecology; Optimization; Energy; Water network;	44 references	2015	[22]

	Mathematical programming			
Eco-industrial parks in Korea	Eco-Industrial Park; Eco-industrial development; Industrial symbiosis; Korea; Industrial development policy	55 references	2016	[29]
Quantitative tools and methods to minimize energy and material consumption in IS exchanges within existing EIPs	Industrial ecology cultivation; Energy network; Energy use minimization; Water network; Retrofitting industrial park; Eco-industrial park	207 references	2015	[23]
Industrial symbiosis and energy strategies within EIPs	Eco-industrial park; Mixed industrial park; Energy management; Carbon footprint	114 references	2011	[30]
Sustainability transition of industrial parks (EIP development)	Eco-industrial parks; Industrial parks; Sustainability transitions; Strategic niche management; Systematic literature review; Case survey	66 case studies out of 115 references	2019	[31]
Academic research on Circular Economy	Circular economy; Sustainability; Industrial ecology; Systematic literature review; Circular business model	565 references	2018	[32]

Supply Chain Configurations in the Circular Economy	Circular economy; literature review; sustainable supply chains; closed-loop supply chains; industrial ecology	77 out of 452 references	2017	[33]
Circular economy concept and applications	Industrial ecology; Industrial symbiosis; Closed-loop; Material flow; Waste management; Resource use	151 references	2017	[34]
Sustainability indicators for EIPs	Sustainability indicators; Eco-industrial parks; Sustainability assessment	68 references	2016	[35]

Table 1. List of relevant literature reviews combining the terms "industrial symbiosis", "eco-industrial parks" and "energy", as returned by the online search. Where the number of reviewed papers is not explicitly provided, the number of references is reported.

As Table 1 indicates, few reviews focus on the energy theme. The development of EIP is analysed in relation to circular economy principles, the industrial ecology paradigm, and the industrial symbiosis approach. Technical, economic, environmental, and social impacts in addition to policy and sustainability implications are taken into consideration. An overview of energy management solutions to reduce the industry related carbon footprint within EIPs was presented by Maes et al. in 2011 [30], with the aim of designing an improved carbon neutrality strategy for industrial parks located in the Flanders Region of Belgium.

Since our preliminary research suggests that no recent literature review has assessed the possibilities of integrating EIP and RES, this paper aims to provide a comprehensive overview of the academic studies focusing on the energy strategies adopted in EIPs. The overview analyses the use of RES and possible urban-industrial synergies in order to identify the research gaps and to design a future research agenda.

Three main factors emerge from the research. Firstly, in terms of the influence of EIP models on energy concerns, the influence of IS approaches in energy management requires further investigation. Secondly, RES are found to be relevant in EIPs. Thirdly the energy management of

EIP has an impact on the neighbouring urban areas. In terms of these three factors, the literature analysis addresses the following questions, illustrated in Fig. 1:

- What types, if any, of industrial energy symbiosis have been devised, planned or implemented?
- To what extent are renewable energy sources used?
- How is urban-industrial energy symbiosis promoted as an integrated sustainable solution involving renewable energy sources?

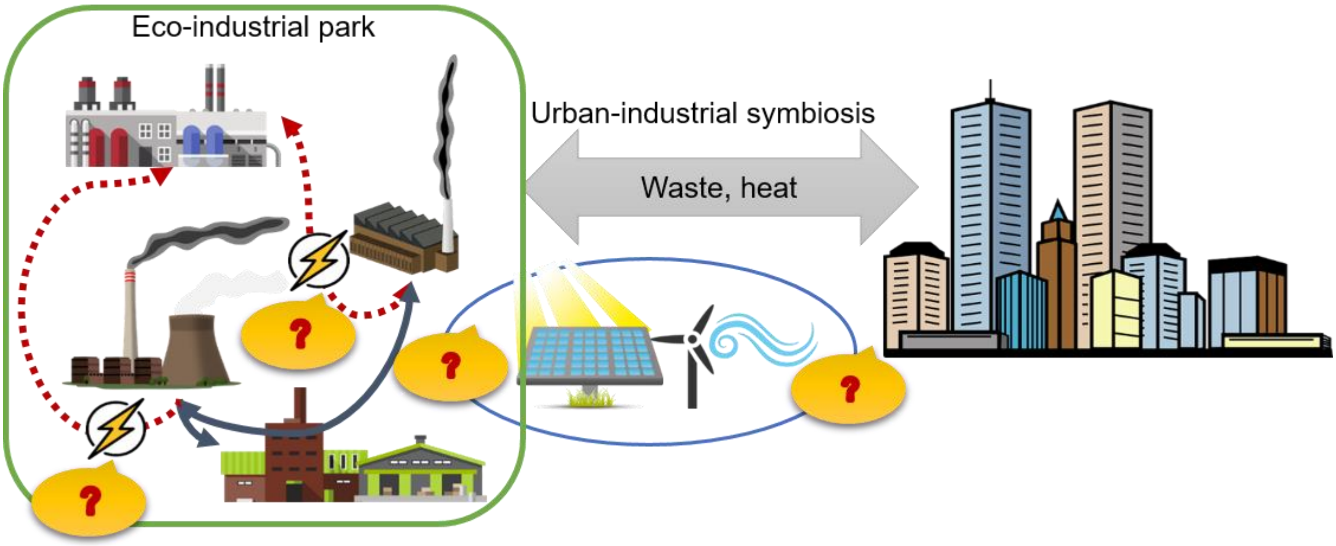

Fig. 1. The research questions.

The illustration of the research questions in Fig. 1 represents the industrial symbiosis (grey arrows) and the investigated potential energy symbiosis (red-dotted arrows) within the EIP. Moreover, the contribution of RES is investigated, supporting energy synergies among firms and urban-industrial symbiosis as well.

3. Review methodology

From the above literature review, we defined keywords for online searches in academic journal articles. The search was conducted using the online databases Science Direct and Web of Science.

In the first step, a list of relevant terms was identified, based on the focal topics: "Eco-industrial parks", "carbon emissions reduction", "industrial energy symbiosis", "renewable energy sources", and "urban-industrial energy symbiosis". We defined temporal boundaries for the review: the literature analysis was limited to articles published after 2010, when technological advancements and declining RES prices led to many techno-economic solutions for the integration of a high proportion of renewables in the energy system [36,37].

After a first exploration of the literature, a broad range of keywords and similar concepts emerged from our initial search terms. Table 2 presents an overview of the concepts associated with our research. The table combines relevant terms through an iterative process of refining the searches.

Initial terms	**Relevant associated keywords and concepts**
Eco-industrial parks	Industrial symbiosis Circular economy Industrial ecology Ecological industry chain Sustainability Eco-efficiency Industrial districts Industrial clusters Industrial synergies
Carbon emissions reduction	Greenhouse gas emissions reduction Low-carbon transition Carbon footprint Lifecycle assessment
Industrial energy symbiosis	Energy efficiency Energy savings Energy integration Inter-firm energy Energy clustering/clusters
Renewable energy sources	Solar renewable energy Multi-generation systems Multi-energy systems Smart grids

	Energy hub Distributed energy resources Storage Community
Urban-industrial energy symbiosis	Urban-industrial synergies District heating Urban energy system transition Eco-town Energy hub Regional multi-energy Community

Table 2. Concepts associated with the initial identified strings of terms that came to light after the first search of the scientific databases.

Using the titles and abstracts, we initially selected relevant papers and excluded those that clearly did not address our research. We then read the full texts of the remaining 291 articles and conducted a snowball search to ensure our research was as comprehensive as possible. A total of 88 papers were then selected as the most relevant. The yearly distribution of the selected papers is presented in Fig. 2.

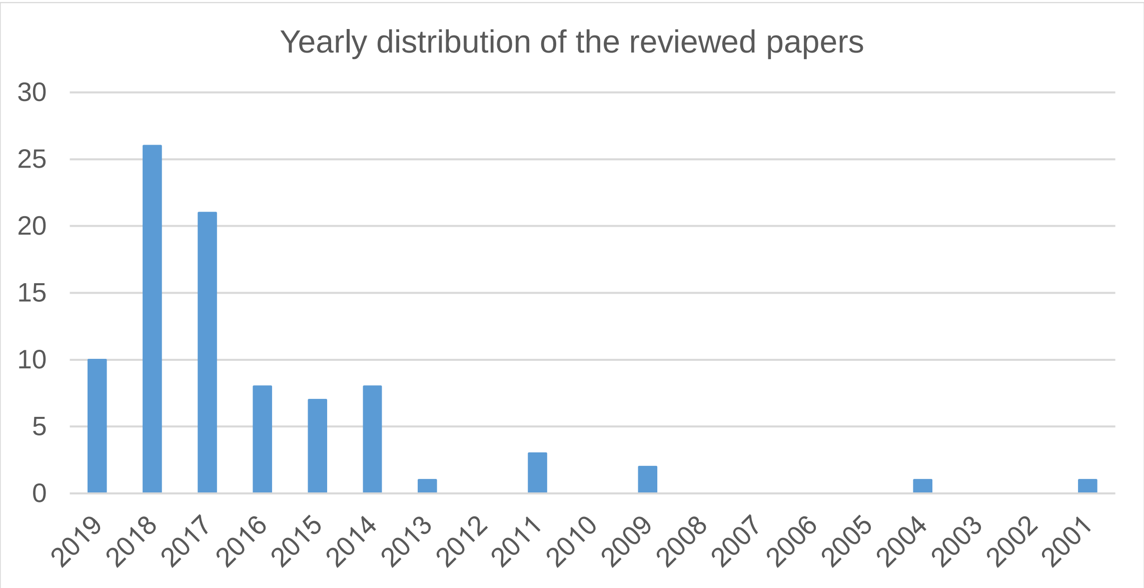

Fig. 2. Yearly distribution of the selected papers.

As illustrated in Fig. 2, the most recent papers were selected to present the most up-to-date research. A few papers outside the set temporal boundaries were included in the review ([38], [39], [40], [41]) due to their seminal relevance to the topic under study.

4. Literature review results – Content thematic analysis

This section presents the results of the performed literature review, arranging the analysed content into thematic categories according to the research questions. The thematic analysis follows the outline illustrated in Fig. 3.

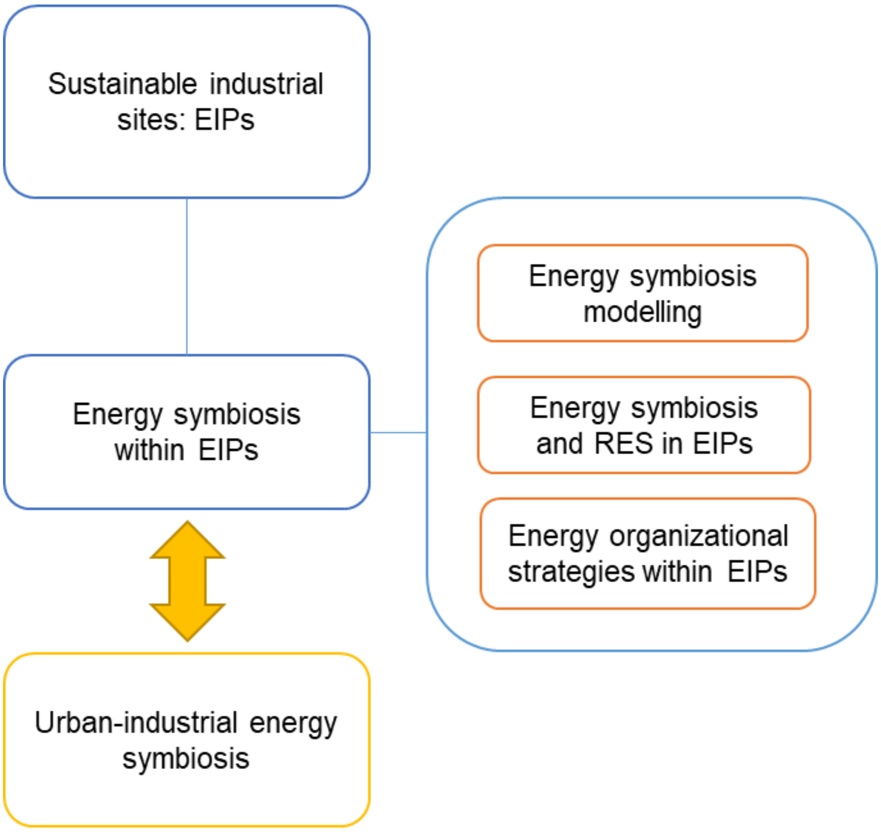

Fig. 3. Thematic outline of the reviewed literature.

Fig. 3 shows the three main constructs that emerged from the literature review: sustainable industrial sites, energy symbiosis within EIP, and urban-industrial energy symbiosis. The sustainability goals set within EIPs drive the creation of synergies among firms. These synergies can take the form of energy symbiosis and promote energy exchanges with local urban areas. The figure also shows a second construct derived from the papers analysis, resulting in energy symbiosis modelling, energy symbiosis involving RES in EIPs, and energy organizational strategies within EIPs. This is the structural axis for the review.

4.1 Sustainable industrial sites: the eco-industrial parks

The need to improve the sustainability of industrial sites is widely explored in the literature, mainly with the aim of developing solutions for reducing the environmental impact at the local level and supporting stakeholders and policy makers. The concept of industrial symbiosis, which has evolved through the academic debate [42–44] and specific projects, represents an effective approach to sustainability in the industry sector. It is considered a part of the industrial ecology field of knowledge [43] as it focuses on the optimization of the materials cycle and fulfils the circular economy principles of reusing, recycling and remanufacturing materials thereby increasing resource efficiency, reducing waste and pollution, and bringing about economic benefits [45].

According to the IS approach, eco-industrial parks are industrial clusters, i.e., a set of industrial companies located near each other, which take advantage of their geographical proximity and consider environment preservation as a key issue when developing cooperation among businesses, thus resulting in economic and social benefits. The network of firms is built on the sharing of resources that include materials, energy, water, infrastructures, and facilities, but also the natural habitat and information, and the exchanges of materials and energy aimed at minimizing the use of resources and the waste generated. EIP projects can be developed from spontaneous cooperation initiatives carried out by companies motivated to improve efficiency and cut costs (bottom-up-model) or promoted by governmental or other institutional initiatives (top-down model) [15]. Lambert and Boons [46] distinguish geographically concentrated industrial activities (mainly process activities with close physical couplings of a relatively small number of materials and energy intensive production processes), mixed industrial parks (where SMEs of different sectors with little coupling of production processes are concentrated in dedicated areas), and eco-industrial regions (referred to as administrative areas where diverse or related industrial enterprises are located).

Techno-economic factors affect the feasibility of EIPs and determine the possibility of creating networking relationships and exchanges among participants, in addition to organizational aspects such as the willingness of individual actors to participate in initiatives [22].

In an integrated approach to sustainability, the EIP is part of a wider system that include the local territory: viable EIPs are also characterized by beneficial interactions with the local community, considering both the social and economic dimensions of sustainable development [17]. Simeoni et al. [47] identify three progressive geographic boundary levels of intervention: endogenous, which refers to solutions designed to improve the sustainability of single activities; exogenous, which refers to solutions designed for industrial zones or parks; and industrial urban systems, which aim to integrate industrial parks into the neighbouring urban territory.

EIPs can be considered as innovation platforms facilitating action concerning environmental impacts, not only with the end-of-pipe approach but also at a systemic level, such as adopting a life-cycle perspective [34]. EIP sustainability according to this view is mainly evaluated in the

literature using life-cycle assessment (LCA) based analysis [48,49], mainly focusing on resources and GHG emissions. With reference to the eco-efficiency concept, as established in [50], the data envelopment analysis (DEA) method demonstrated its efficacy and is widely used to assess the sustainability of industrial parks. The relative eco-efficiency of industrial parks in China was analyzed by Fan et al. [51] who compared the factors influencing the eco-efficiency. Pai et al. [52] designed an eco-efficiency measurement model for EIPs in Taiwan, as a tool to be used for the continuous improvement of sustainability. Wang et al. [53] developed a methodology for the optimal design of the ecological industrial chain within EIPs based on the DEA method.
Other methods, recently applied to evaluate the environmental efficiency and the GHG emissions of industrial processes and parks, are based on emergy analyses, considering the quality of each form of energy flowing through the system [54].

The sustainability objectives of EIP projects has been extensively studied, beginning with the Kalundborg industrial district in Denmark, which is considered a forerunner of the eco-industrial parks, because of the inter-firm and urban links initially developed to take advantage of an excess of energy [55]. Heeres et al. [56] investigate successful implementations in the US and the Netherlands. Chertow and Ehrenfeld [42] analyse a number of existing EIPs to derive a model for self-organizing systems.

Many recent papers study the results of various national programs supporting EIPs development: Park J. et al. [29] investigate the sustainability progress achieved by the first phase of the Korean EIP program, Huang et al. [57] review China’s EIP system to provide tools for assessing EIPs, and Pilouk and Koottatep [58] study the Thai EIPs projects for developing a set of sustainability indicators suitable to promote EIPs. Domenech et al. [45] reported an overall updated overview of IS activity in Europe in their review, which was supported by the European Commission’s funded research projects.

Energy, that is closely related to environment and sustainable growth, is a key theme when assessing industry sustainability objectives. Valenzuela-Venegas et al. [35] review a set of indicators for assessing the sustainability of eco-industrial parks in terms of energy. They list at least 20 possible indicators directly related to energy, many of them considered from the environmental point of view. To clarify the focus of these energy-related indicators, they have been categorized in Table 3 as energy efficiency, emission-related, energy consumption-related and resources use-related indicators (including energy).

Category	Indicator	Definition	Sustainability dimension
Energy efficiency	Energy consumption per	The energy efficiency of the candidate enterprise by calculating of all the	En

related indicators	unit	energy and converting to the number of standard coal using means conversion coefficients	
	Output rate of energy	The amount of production value in EIP generated from one unit of energy	En/Ec
	Energy consumption per unit of production value	The level of efficient use of energy in a firm	En
	Energy consumption per unit of production in the key industrial sector	The level of efficient use of energy in the key industrial sector	En
	Energy intensity	The energy consumption efficiency. It relates the consumption to the output of the sector in monetary values	En
	TEIw	The TEI per number of workers	En
Emission related indicators	Direct energy consumption carbon footprint	This refers to emissions from the direct combustion of fossil fuels within the administrative boundary	En
	Electricity and heat carbon footprint	This refers to the indirect carbon footprint in terms of purchased electricity and heat purchased out of the park	En
	Specific emission	The total CO_2 emissions related to the energy consumption	En
Energy consumption	Energy carrying capacity	The possibility of meeting the energy demand of the candidate enterprise in an EIP	En
	Percent-added	The growth rate of energy production	En

	of park energy productivity	in the park after the introduction of a new business	
	Energy consumption per added industrial value	The energy consumption including coal, electricity, oil, and energy consumption for both heating and cooling	En/Ec
	Total energy consumption intensity	Sources of energy such as coal, electricity, oil and other energy consumption (including the production of heating and cooling energy) used for the production and operation of the enterprise	En
	TEI	The amount of energy consumed by the system and subsystem, differentiating between energy generated domestically and energy imported	En
	Energy consumption indicator	The total energy consumption of a park	En
	Energy intensity	The sum of the total amount of energy	En
	Primary energy	The contribution of a material of a process to the primary energy	En
Resources use (including energy)	Resource use	This considers the three main resources of water, land, and energy	En
	Resource use efficiency	This is based on the overall resources including energy sources	En
	Renewable resources input	The total energy and material driving a process that is derived from renewable sources	En

Table 3. The main energy related indicators used in the literature for the sustainability assessment of EIPs (adapted from [35]. (En = Environmental; Ec = Economic)

Table 3 shows that a sustainability indicator considering the share of renewable energy and/or use within a park is not explicitly defined in the reviewed papers. Wang et al. [59] suggest an index system to evaluate the stability of the EIP network from the very beginning of the project including the renewable energy use ratio, i.e., the proportion of energy produced by renewable sources used by companies. This index considered an indicator of energy sustainability, is applied to assess the admissibility of a company to an EIP. According to this view, the new Chinese EIP standard system (set in 2015) introduces a new sustainability indicator “Usage rate of renewable resources” [57], as well as the Vietnamese programme that uses the share of energy produced by renewables as a key indicator for the EIP sustainability evaluation [60].

4.2 Energy symbiosis within EIPs

In terms of industrial symbiosis, the electrical and thermal energy flows and the material flows among firms are designed with the aim of reducing the overall energy use and improving the air quality. Unlike material exchanges, which are specifically related to the industry sector of the involved enterprises, the energy symbiosis within EIPs can be approached in a more general way to develop technical and organizational strategies that can be compatible with mixed industrial parks and can comply with new or existing parks.

The energy use within an industrial site can be assessed detailing the activities conducted as industrial use (production-related equipment, including service facilities), building services use (utilities such as lightning, heating and cooling, safety systems, and transportation systems) and civil use (office buildings) [61]. The analysis of the thermal and electrical needs of companies and the comprehensive evaluation of energy inputs-outputs for all industrial processes enables an energy baseline to be calculated and defines where inter-plant or inter-company connections can be established.

In addition to inter-firm energy exchanges, joint projects for energy efficiency and for collective energy production can be implemented. Since the work of Fichtner et al. [38], different inter-firm energy supply concepts have been investigated as promising approaches for achieving cleaner energy production. In addition, EIPs are often already equipped with energy infrastructure for the transformation of waste materials into heat and electricity, which can be supplied to the enterprises joining the park or uploaded to the local power grid.

The energy symbiosis in EIPs is further investigated below according to the three constructs: the modelling approaches, the use of RES and the organizational strategies. This section answers the first two research questions, as represented in Fig. 4: the energy symbiosis within EIPs are investigated and the contribution of the RES is highlighted.

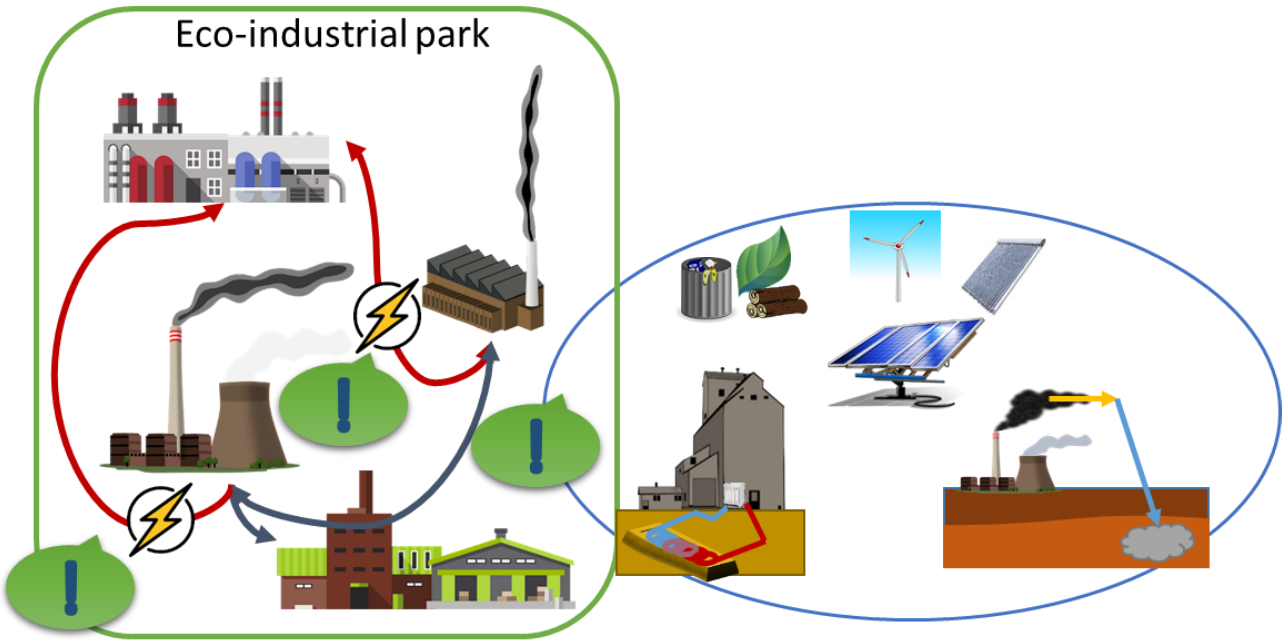

Fig. 4. The main renewable energy conversion technologies integrated within EIPs: waste/biomass treatment plants, wind turbines, solar panels (thermal collectors and photovoltaic plants), ground-source heat pumps. The carbon capture and storage (CCS) technology, used to prevent carbon emissions in the atmosphere is also depicted.

4.2.1 Energy symbiosis modelling

From a modelling point of view, the design of EIPs can be treated as a multi-objective problem because it involves numerous stakeholders with potentially conflicting objectives and a mix of technical, environmental and social issues. Techno-economic and environmental issues are the most addressed, while organizational and social aspects have been only recently considered [22].

Energy symbiosis modelling can be viewed as an aspect of EIP design. Most optimization methods used in the design of EIPs separately consider the types of symbiotic relationships, i.e., materials, energy, and water [22]. Some studies investigate interplant energy flow management, mainly using pinch analysis or mathematical programming approaches, and only a few address energy management in an EIP through mathematical optimization. Kastner et al. [23] reviewed modelling methods to identify and establish viable inter-company exchanges; pinch analysis and mixed integer linear programming are the main methods used to optimize energy (mainly heat) exchange networks.

Energy symbiosis models mainly aim to simultaneously minimize costs and emissions related to energy exchanges [62], and to optimize energy efficiency. Technical features should be taken into account, and both EIP advantages and the individual benefits should be considered [63]. Timmerman et al. [64] first compare energy models and then discuss a classification for them, to design a low carbon energy system within EIPs, suggesting a holistic techno-economic modelling approach. A low carbon energy system includes energy efficient technologies, maximizes the integration of local renewable energy sources and enables heat exchange between firms. Some of the features that a suitable energy system model should include are:

- multi-objective optimization, to facilitate the trade-off between conflicting objectives, such as minimisation of both costs and carbon emissions;
- a generic technology description at unit level;
- sufficient temporal detail, showing energy demand and RES availability trends and peaks
- energy storage technologies and flexible energy demands
- heat flows characterized by temperature-heat profiles and an intermediary heat transfer network
- the system superstructure, which enables the introduction of any energy service demand or energy production technology

4.2.2 Energy symbiosis involving RES in EIPs

The potential for renewable energy use in industry has been widely explored in terms of supporting sustainable development and fostering the low carbon shift in the manufacturing sector. Technical and economic and environmental assessments demonstrate the benefits of possible integration [65]. The main renewable energy sources suitable for industrial application are biomass, solar radiation, ground heat, and wind. The right renewable energy technology or technologies need to be chosen, as well as the size of the plant based on the SMEs' energy demands and profile, and any overproduction handled [66]. The investment efficiency of different RES technologies and the best energy strategy can be evaluated with DEA methods [67,68].

This subsection describes the options and current solutions for RES integration in EIPs. Fig. 4 shows the RES integrated within EIPs according to the reviewed papers: waste/biomass treatment plants, wind turbines, solar panels (thermal collectors and photovoltaic plants), ground-source heat pumps. The carbon capture and storage (CCS) technology, used to prevent carbon emissions in the atmosphere and calculated as negative emissions in the CO_2 emissions assessment, is also shown. Multi-energy systems architectures, including RES, were the most explored and effective option.

Energy symbiosis within EIPs creates exchange networks that can be classified, according to Afshari et al. [63], based on the source of supply. In the first type inter-firm energy waste can be used to supply internal energy demand; in the second type, a set of energy hubs satisfies the energy demand of the involved partners; and in the third type, waste or unused energy (from processes) are shared among companies. According to the authors, this last type of network maximizes the environmental impact reduction.

Thus, heat exchanges between processes can be considered as a first level network designed to optimize energy use; the further step, including exchanges via a central utility system, requires heat exchangers and intermediate fluid [23]. In addition, the excess heat can be supplied through a direct inlet into the district heating network or converted into electric energy by means of a proper conversion technology, avoiding the discharge of heat into the environment [69]. The low temperature heat (below 200°C) is referred to as "waste heat" as it is not directly recoverable in industrial processes. Industrial waste heat can be recovered from flue gas, cooling fluids and exhaust steam. The available and effective technologies to recovery the low-temperature waste heat produced by industrial processes and utilities can be either upgrading technologies, to produce thermal energy for heating or cooling, or converting technologies to convert the waste heat into electric and mechanical power [70]. Industrial heat recovery options are illustrated in Fig. 5.

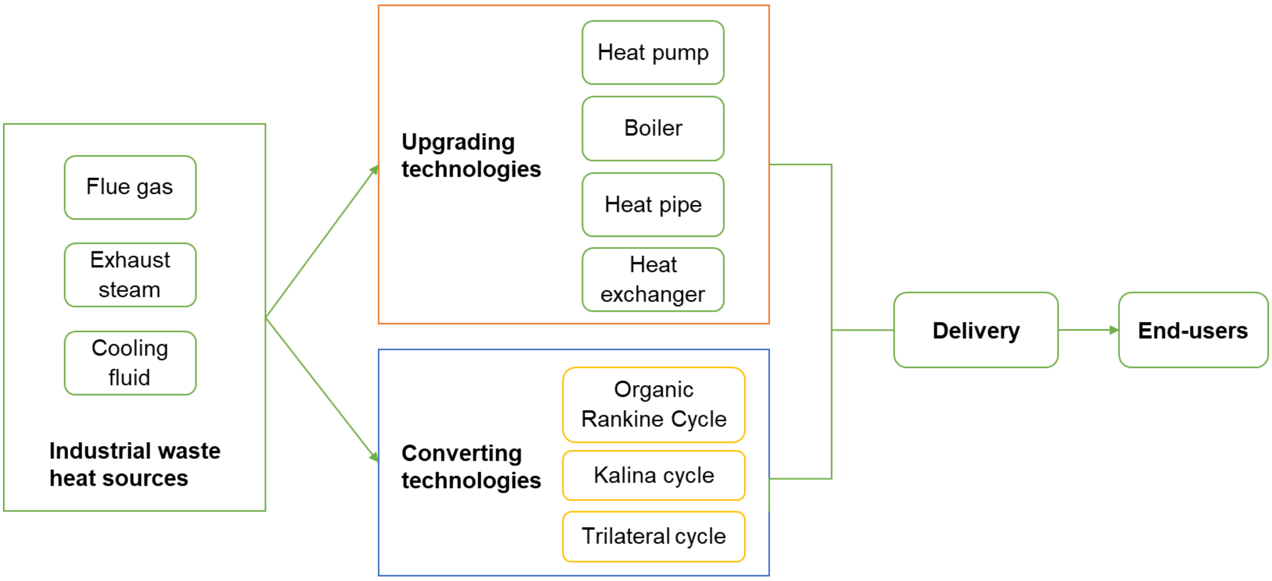

Fig. 5. Industrial waste heat recovery options (adapted from [70]).

Heat exchangers, heat pipes and condensing boilers, which are upgrading technologies detailed in Fig. 5, are typically used for recovering waste heat that can be reused internally in the industrial process. Heat pumps can be effectively used in the case of district heating. The waste heat recovering for power generation by means of low temperature engines (the Organic Rankine Cycle, Kalina cycle and trilateral cycle) is mainly effective at medium to high temperatures (100°C-200°C).

The recovery of industrial waste heat is suggested by Marchi et al. [71] to improve sustainability of the Brescia (IT) industrial district, through a direct inlet into the district heating network and through electric energy conversion. The presence in the EIP network of a multi-utility operating in the energy sector allows the companies that produce surplus energy (electrical or thermal) to also sell it to the multi-utility itself for satisfying shared utilities or the local urban area demand. Sludge and waste wood can also be treated to produce fuel.

Organic waste materials are considered the most sustainable biomass supply for energy production, and are a frequently used within industrial parks for recovering waste that cannot be otherwise reused or recycled, thus avoiding landfill ([72], [73]). This includes anaerobic digestion, incineration (direct combustion followed by energy recovery of the heat generated), gasification and pyrolysis. Waste treatment plants are often shared with municipalities so urban waste can also be collected, and represent the most widespread example of synergy between an industrial park and the neighbouring urban area.

The pulp and paper industry is a major industry sector in Finland, and produces waste materials such as bark, wood chips, fibre suspension and milled peat. Sokka et al. [74] evaluate the GHG emissions of the Kymi EIP, where a power plant uses the scraps of the main pulp and paper plant as fuel to generate steam, electricity and heat, which are then delivered to the pulp and paper plant itself, to chemical factories located within the park, and to a regional energy distributor. The authors, through their LCA based analysis, find that emissions would increase by 40-75% if the materials and energy exchange had not been implemented.

Many case studies demonstrate that energy exchange relationships among companies within an EIP lead to a collective GHG emissions reduction. Park et al. [29] reveal that among the 116 implemented during the first phase of the Korean EIP program, 21 projects involved various types of energy recovery such as the use of residual heat from waste incineration or anaerobic digestion and heat recovery from by-products. Ban et al. [75] demonstrate the carbon dioxide direct emissions reduction in commercialized eco-industrial park projects in South Korea, listing the projects aimed at reducing fossil fuel use through the creation of energy networks for energy recovery and waste treatment plants for power generation.

The type of fuel used in shared power plants and heat supply systems significantly affects the level of carbon emissions within the parks [76]. For power plants or energy intensive industries are present, carbon capture and storage technology can help to prevent carbon emissions in the atmosphere. CCS is a recognized technology promoted by the European Union which together with carbon capture and use (CCU) can be used to reduce the carbon footprint of power and industrial sectors. The capturing systems depends on the combustion processes [77] and, after the capturing phase, carbon dioxide can be transported and stored in geological formations such as deep saline aquifers and oil or gas reservoirs. Technologies for reusing captured CO_2 where geographical constraints make storage sites non-viable are explored by Koitsumpa et al. [78]. They present potential uses of CO_2 for fuel and for combined heat and power production in industrial applications.

The introduction of electricity generation plants fuelled by RES within EIPs affects the indirect CO_2 emissions, due to electricity acquired from external suppliers. When also considering the production of thermal energy from renewables, there is also an impact on direct emissions [39]. Guo et al. [79] evaluate the GHG mitigation potential of actions aimed at targeting energy consumption for 213 Chinese industrial parks. The study, through a process-based LCA method that assesses direct and indirect energy-related GHG emissions, shows how the implementation of three measures can bring about significant GHG emission reduction: (i) increasing the share of natural gas and (ii) the efficiency of industrial coal-fired boilers, which have an impact on direct emissions, and (iii) reducing the GHG emission factor of the electricity grid, which has an impact on indirect emissions. The latter can be achieved through low-carbon energy production and upgraded energy infrastructure within industrial parks. Feng et al. [80] compare three low carbon scenarios that can be applied to a Traditional Chinese Medicine industrial park. Assuming that energy conservation measures are implemented, the scenarios include clean energy plants (biomass boilers and photovoltaic (PV) solar energy) with high capacities, which result in a greater carbon emissions reduction, even if the cost effectiveness of such a solution involves the reduction of the solar energy cost.

Despite the major academic efforts to demonstrate the feasibility and effectiveness of the use of renewable energy sources within EIPs, progress is still slow, as reported by Guo et al. [81] in their study involving 106 Chinese EIPs participating in a national demonstration program to facilitate the eco-transformation of industrial parks. They classify the energy infrastructure of the parks by assessing the direct GHG emissions of the power plants, as they represent the main direct GHG emission source. Only 3 EIPs out of 106 share RES power plants: one solar power station with distributed geothermal heat pumps and two solar power stations. In total, the renewable-fuelled power plants (biomass, bioenergy, solar, wind, hydro and geothermal) account for about 1% of the total power generation capacity.

Energy-savings solutions (relighting, insulation) and an increase in electricity and heat produced by means of renewables are suggested by Block et al. [82] to achieve carbon neutrality at the Herdersbrug Industrial Park (Belgium), where the main CO_2 emissions are due to energy consumption and the waste incineration plant. The evaluation shows that about 67% of total CO_2 emissions can be compensated for by the existing and projected renewable energy generated in the park. Renewables plants are already present in the park, in the form of wind turbines and PV panels that cover the roof of two companies (16,000 square meters). The flat or saw-tooth shaped industrial buildings represent a typically unused and exploitable area for installing wind or solar energy generators.

The use of RES is conditional on the local availability of the source and solar resources (including wind) vary with the time of the day, the season and the weather. When the main energy utilization period is during the daytime, the energy demand matches the supply, maximizing the exploitation of solar energy. The patterns of solar energy utilization for energy supplies in industrial districts located in Yunnan Province in China is investigated by Su et al. [83]. They apply a multi-objective optimization approach to find the optimum solar hybrid energy systems, in which the global warming potential and life-cycle economic cost are minimized, while optimizing the exergy performance of the system. The high cost of electricity for industrial use and the large energy utilization during the daytime leads to the evaluation of solar energy technologies, and particularly low-temperature thermal energy generators, which are more competitive in industrial districts than in residential areas. When the solar energy availability does not match the energy demand, due to energy utilization patterns or weather induced intermittency, energy storage solutions or the use of auxiliary energy technologies are required [84].

An effective method of increasing the RES utilization efficiency at the industrial park level is to combine heat and power generation through the use of combined heat and power (CHP) systems. CHP systems simultaneously generate electricity and useful heat that can be used for heating buildings and supplying hot water. They also allow for the recovery of heat generated by electricity production, resulting in an overall efficiency approaching 90% [85]. CHP plants can be fuelled by various energy sources, including waste and renewable sources such as biogas, biomass and solar and can contribute to diversifying the energy mix of a district. Due to these characteristics, CHP plants support recycling networks and can facilitate both inter-firm cooperation and urban-industrial synergies, and they have long been recognized as meeting the principles of industrial ecology [40].

Solutions such as CHP with the use of ground probes for thermal storage and building integrated photovoltaics (BIPV) can be considered effective options for augmenting energy flexibility in manufacturing environments, and particularly in technical building systems and auxiliary processes, facilitating the use of renewable energy sources and improving the sustainability of industrial processes [12].

The use of various renewable energy sources for generating both electricity and heat (hybrid-RES), and in combination with other generation systems such as tri-generation technologies (combined cooling, heat and electricity), energy storage systems and energy distribution networks, enable the configuration of a smart multi-energy system (SMES or smart-MES) as represented in Fig. 6. Smart-MES can be modelled to support decision-makers in identifying and choosing the better generation options including RES [47]. The concept of smart-MES (sometimes called Smart Multi-Energy Grids) extends the concept of the smart-grid [86], typically defined within the limitations of the electricity sector, by integrating multi energy carriers. Applying the smart-grid architecture enables the discontinuity of renewable sources such as solar or wind to be managed. The main characteristics of smart grids are the use of ICT and smart technologies for controlling and managing the grids and the integration of distributed energy resources (DER). DER are considered to be the main pathway towards an effective integration of discontinuous sources into the energy system, and involve small-scale units of local generation connected to the grid at the distribution level. The DER configuration typically includes storage solutions and demand-side resources (load management systems, energy efficiency options), and allows a two-way flow of power between the decentralized grid and the main distribution grid [87]. Depending on the energy demand end-uses the optimal combination of DER technologies can be evaluated using DEA models, to compare and calculate the factor efficiencies of each energy technology for each end use [88].

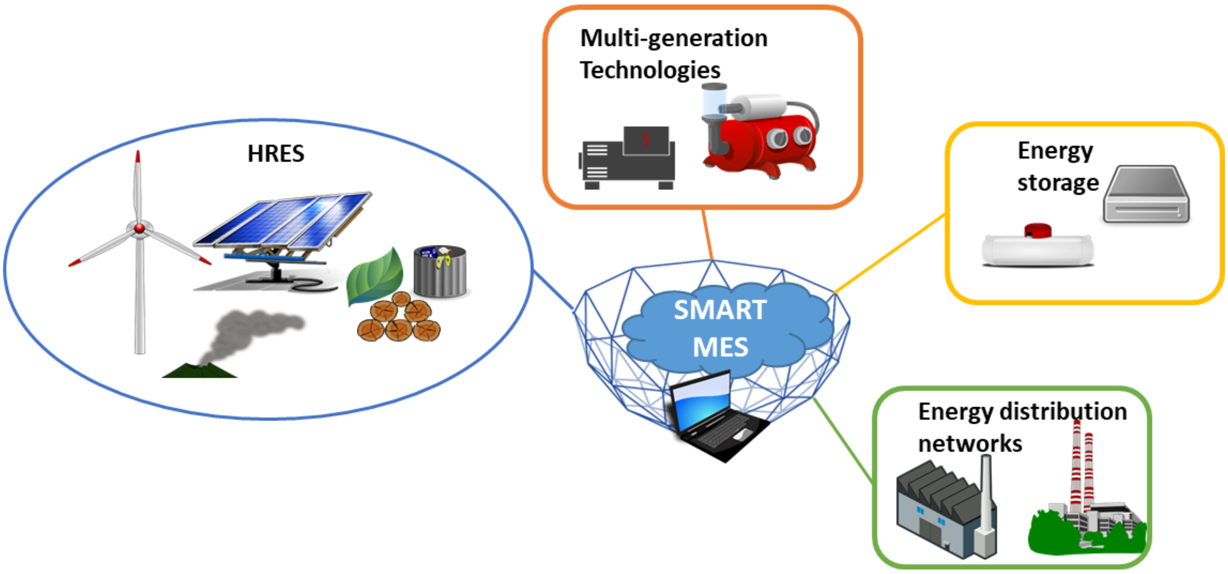

Fig. 6. The smart multi-energy system concept, enabling the smart control and management of the grids and optimizing the use of distributed energy resources.

EIPs internal utility networks can be viewed as small-scale grids and, as they are generally interfaced with the main utility network through a single point of common coupling, they can be considered as microgrids. Industrial smart microgrids, consisting of inter-connected loads and DER including RES, can be developed and operated in a controlled and coordinated way, optimizing the control of the individual units and the grid itself. A smart MES configuration promotes a coordinated energy strategy within EIPs. According to Deckmyn et al. [89], within the energy management system, the microgrid control architecture can be centralized or decentralized. A centralized controller optimizes the exchanged power between the microgrid and the utility grid by maximizing the local production, gathering data from every DER within the microgrid; it is highly efficient, but due to the complexity of the system a single point of failure may arise. A decentralized management system uses local controllers that work autonomously, controlling specific DER units, but in a coordinated way with other local controllers to improve the overall performance of the microgrid. They maximize their production to satisfy the demand and provide the maximum possible export to the grid. Within industrial parks the loads have different owners, as may the generation and storage units, so decentralized control can be the preferred solution.

The energy management system of a micro-grid consists of a supervisor [90] who optimizes the power flow within the system. The first stage involves forecasting the inputs required; then the system solves the optimization problem by establishing the state of all the equipment; lastly it sends control signals to the power generation devices. Many micro-grid energy management systems have been studied in the literature [91], employing various decision making strategies and solutions.

Reynolds et al. [92] suggested using multiple artificial neural networks (ANNs) to perform both supply and demand optimization at the district level in order to manage demand-side flexibility in a smart multi-energy context. An ANN is used for weather forecasts and the prediction of the energy consumption [93] and power output of generation sources [94]. ANN methods are widely used to manage RES intermittency within the distribution system [95], and are applied in forecasting, design optimisation, fault detection and optimal control [96]. They estimate/forecast solar-related variables (such as solar radiation and clearness index), atmospheric-related variables (such as wind speed), hydrologic-related variables and geologic-related variables. The combination of these variables enables the optimal management of RES [97] and the balance of energy exchanges with the main distribution grid [98].

A suitable tool for the integrated management of a smart MES can be modelled as an energy hub (EH). Mohammadi et al. [99] defined this as “the place where the production, conversion, storage and consumption of different energy carriers takes place”. An EH is in essence an interface between primary energy sources and end-users, incorporating energy conversion and storage processes. A typical energy hub uses input energy carriers (electricity and natural gas), energy converters (transformers, gas turbines, gas boilers, electrical chillers and absorption chillers, and RES converters), energy storage devices and provides electricity in addition to heating and cooling energy services as the outputs. A schematic diagram of the energy hub concept is depicted in Fig. 7.

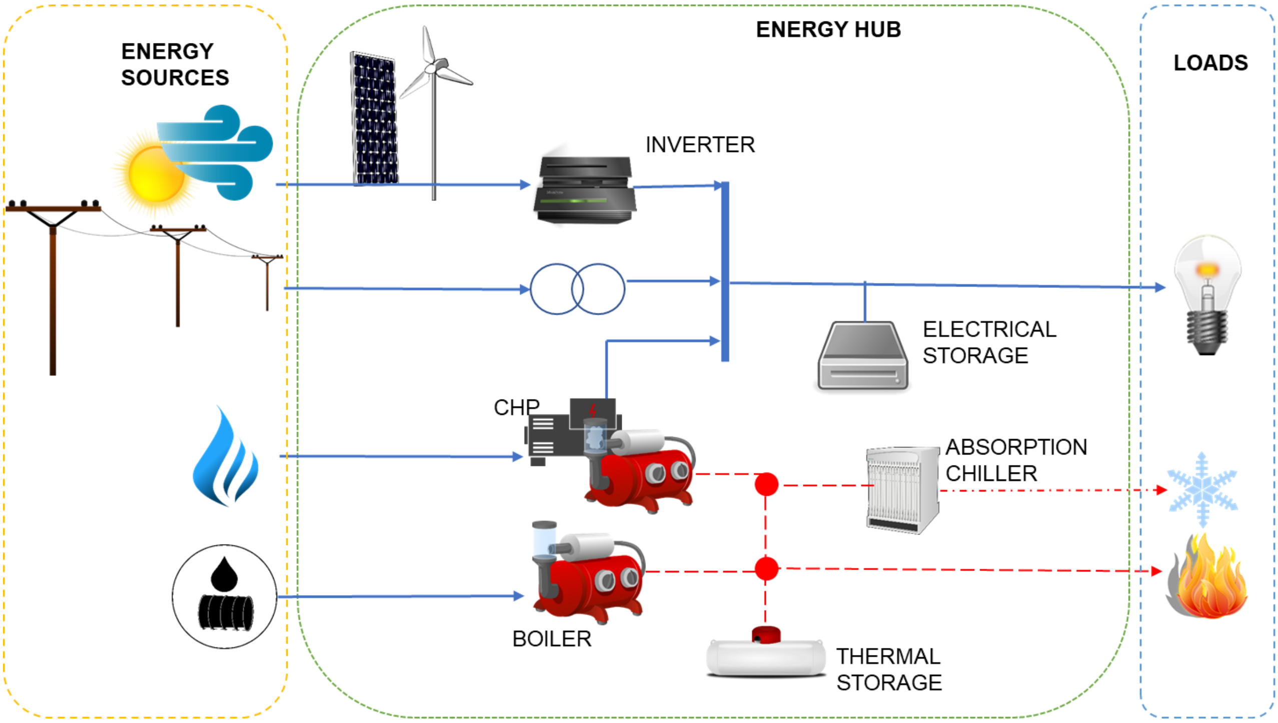

Fig. 7. The energy hub (adapted from [99,100])

As Fig. 7 shows, within the EH different energy sources are converted using suitable technologies. The efficient use of multi-generation systems allows the use of the energy resources to be optimized, increasing the efficiency and reducing emissions and costs [101]. A similar concept to EH is outlined by Xing et al. [102] in the modelling of a distributed energy system. They applied a multi-objective method to the design of a DER system within an EIP, considering the natural gas allocation scheme between industrial parks to manage gas shortages.

Another aggregation concept for DERs is the Virtual Power Plant (VPP), a cloud-based control centre that uses communication technologies to gather data from distributed power plants, controlling and managing generated power and energy flows. It emulates the functions of a traditional power plant, enabling small distributed energy resources to participate in the energy market. Although this approach had been developed mainly for addressing distributed electrical resources managing, it is also well suited to multi-energy applications [103].

4.2.3 Energy organizational strategies within EIPs

As discussed in the previous subsection, a multi-dimensional mix of technological options is available to improve the energy efficiency and autonomy of an EIP. Energy efficiency measures, both at the industrial operational level (more efficient processes and machineries, introduction of heat exchangers and fuel switching to renewables) and the buildings level, and energy conversion systems using available renewable sources are effective choices for reducing the amount of imported energy into the park. In addition, if a joint planning strategy and management is developed, the interventions at park level can result in greater GHG emission reductions than would be possible through individual reduction interventions [104].

The key factors for facilitating the distribution of renewable energy technologies are the information available to potential adopters, the interaction of involved actors and the existence of a critical mass (firms' agglomeration) to reduce costs. In addition, the concentration of many firms in the same location enables them to take advantage of common services and common service providers [14]. Thus, the planning and managing of EIPs should include a collective energy strategy stimulating the use of renewable energy, through the purchase of RES generated electricity, individual or collective self-production of green electricity, energy cooperation among industries through infrastructures sharing [30]. Timmerman et al. [64] present an EIP energy system scheme where individual companies can be either connected to energy conversion units or to an internal energy network with storage facilities, supplying a number of companies. The local network can be connected to both the regional distribution grid and the district heating (DH) network.

Feng et al. [80] introduce the concept of the zero carbon industrial park (ZEIP), where the inventory of energy demand and supply, carbon emissions, and negative emissions, are considered. In addition to direct and indirect carbon emissions, a carbon offset term is introduced, to account for clean energy supply, energy conservation, and negative emissions (e.g. carbon capture and storage), and, once the park energy consumption and emissions are known, the energy strategy can be designed to maximize the carbon offset. Within the proposed framework for the implementation of the ZEIP scheme, the management and technical levels are separated. The management level includes the selection of the participant enterprises, the energy management, and the monitoring of energy consumption and carbon emissions. The technical level includes the technical measures to improve energy efficiency, balance energy demand and supply and balance carbon emissions and offset. The technical measures aimed at maximising the carbon offset are illustrated in Fig. 8.

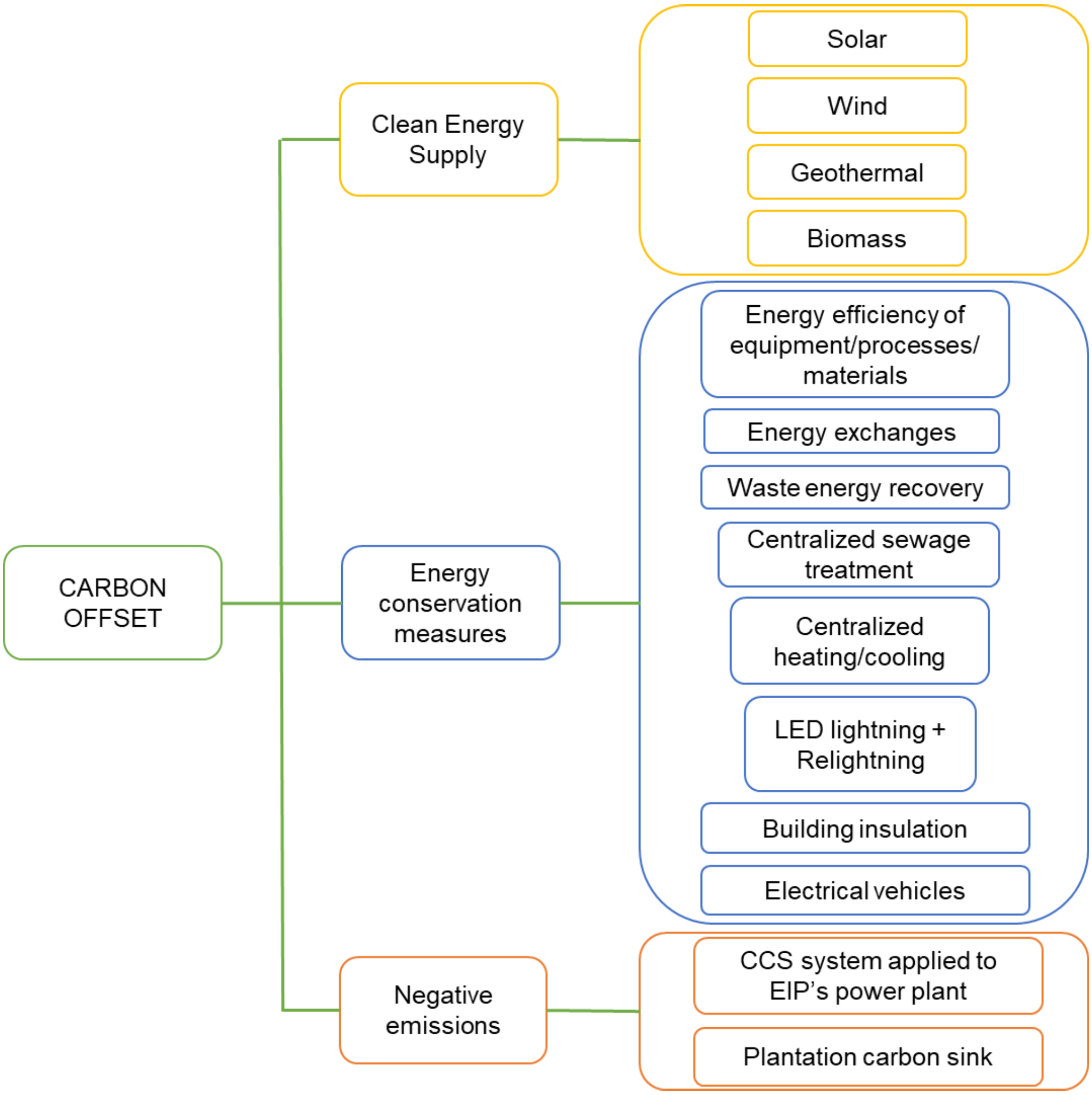

Fig. 8. Carbon offset maximization technical measures (adapted from [80])

The selection of the technology to be included in the carbon offset scheme is based on a comprehensive evaluation of profitability, the carbon reduction potential and the social impacts. The introduction of RES to improve the carbon offset can be managed by a central energy server, which is responsible for technical guidance, system management, in addition to equipment and grid maintenance. Energy conservation includes a wide range of measures such as improved process efficiency, energy recovery and energy saving solutions. Negative emissions are calculated for plantations.

Hentschel et al. [105] discuss the introduction of renewable energy cooperatives, as a form of clustering involving firms and other local stakeholders to foster the deployment of renewable energies within industrial clusters. A renewable energy cooperative composed of companies can be seen as a strategic alliance, in which they can manage market uncertainty linked to RES investments, improve energy efficiency, reduce their dependence on external energy suppliers, get together the required skills and resources, and exploit the available solar energy. The study identifies the specific characteristics of a cooperative required for facilitating the energy transition of the Port of Rotterdam, one of Europe's major industrial clusters, but it can also serve as support for other clusters' stakeholders. Organizational issues, clear targets and milestones, trust and close communication among partners are the main attributes required for a successful project. There needs to be a trade-off among the potentially conflicting objectives of the stakeholders involved in creating energy symbiosis, for example reducing investment costs vs reduced environmental impact [106].

The benefits of setting an energy strategy at EIP level are summarized in [30] and [38]. Energy clustering can provide many benefits for participating companies: it enables the investment costs for plants and infrastructures installation to be reduced, along with the operational expenditure (fuel, maintenance). It also provides favourable prices for collectively purchased utilities and a more even load curve by bundling the energy demands of the different firms, reduces their dependence on energy market prices due to the sharing of the energy produced, and results in reduced taxes and improved brand images, due to the lower carbon footprint.

4.3 Urban-industrial energy symbiosis

In addition to the industrial symbiosis concept, the concept of urban-industrial symbiosis has emerged. In their analysis of the development of IS and the related practice in Japan, Van Berkel et al. [41] identify the emerging of the urban-industrial symbiosis concept in relation to the Japanese Eco-Town Program. This Program (which started in 1997 and ended in 2006) extended the focus of industrial sustainability from industry eco-efficiency initiatives to industrial symbiosis and urban-industrial synergies.

Some types of industrial sites are equipped with waste/sludge treatment facilities that can also use urban waste as fuel, improving plant saturation and reducing waste landfill and thus bringing advantages both to industry and neighbouring urban areas. This kind of synergy is the basic UIS approach. Urban areas deliver urban solid waste for incineration or recycling, urban organic waste for energy production (e.g., by anaerobic digestion, pyrolysis, and gasification) [107], waste water for treatments, sewage sludge for energy production [74], and receive back electrical or thermal energy from industrial clusters. However, urban areas also play an important role in energy consumption and carbon emissions and EIPs can provide clean energy to local communities, thus improving the social role of industry [19].

Different approaches to urban-industrial symbiosis emerge from the literature. Industrial parks can be located near already established cities, or as in China, rapid industrialization starting from the 1980s lead to the establishment of large-scale industrial districts followed by the growth of related urban districts, which now face strong environmental degradation. A Chinese national EIP program was launched in 2001, supporting the eco-transformation of industrial parks towards comprehensive eco-cities, mainly through the implementation of energy efficiency and pollution reduction measures. During the 2010s, low carbon and sustainability issues encouraged further interest in urban-industrial energy synergies.

Dong et al. [19] analyse the advantageous relationships between industrial parks and urban communities that have achieved a successful low-carbon strategy. By focusing on ongoing projects in China, they note that material symbiosis (mainly urban waste recycling systems) is more common than energy symbiosis, mainly due to the physical characteristics of energy being more unstable to transport and requiring costly transportation facilities. However, the further opportunity to reduce GHGs emissions in industrial areas in China makes urban-industrial energy symbiosis a solution that is also assessed and promoted through policy support, as technology innovations can enable more energy efficient transportation, and information platforms enable the collection and exchange of information regarding material/energy/waste flows. The case study they investigate, regarding the urban-industrial symbiosis at the cities of Jinan and Liuzhou, demonstrate the CO_2 emissions reduction potential of this type of project.

The urban-industrial symbiosis of the Suzhou Industrial Park and Suzhou City energy efficiency solutions, in combination with the funded integration of clean and renewable energy solutions (such as CHP, water/ground source heat pumps, solar water heaters), led to clean energy accounting for 78.6% of the total usage in 2012 [108].

The Eco-town program developed in Japan aimed at promoting advanced urban planning in accordance with the zero-emission concept: in particular, it fostered industry synergies focusing on the reduction of industrial waste and material recycling and supported the development of plastic and electrical appliance recycling facilities in many eco-towns. Only two Eco-towns [76], Kawasaki and Kitakyushu, feature energy exchange by using waste heat from the industrial district.

Kim et al. [109] focus on energy symbiosis networks, analysing a urban-industrial symbiosis scenario linking the Onsan and Ulsan-Mipo national industrial parks to Ulsan city (South Korea), to evaluate the environmental and economic benefits of re-using industrial waste heat at both industrial and urban levels. Two recovery systems are proposed: a pipeline for waste steam exchanges between industries and a central heating system collecting the industrial waste heat for heating and cooling purposes of the residential and commercial area. The potential of sending municipal waste to the incinerator plant to generate heat for industrial use and to a digester to produce methane for fuelling electricity generators is then considered to complete the UIS framework. Environmental and economic benefits can be demonstrated through this energy symbiosis by sharing the costs of the initial investment at EIP and public levels.

Focusing on the Fukushima region after the 2011 earthquake, Togawa et al. [69] discuss the need for the effective recovery of underused thermal energy, like waste heat, to provide sustainable energy sources that reduce the environmental impact on local urban areas. They consider the concept of energy symbiosis essential at the regional energy planning level, based on the idea of industrial symbiosis, for implementing energy exchanges between factories and between factories and residential/commercial areas, in a district heating (DH) model. In the consideration of heat transfer systems, the proximity of energy consumers to suppliers is a key design factor.

District heating is a flexible technology enabling the use of many fuels or sources of heat; it comprises a network of pipes connecting the buildings to be heated and/or cooled, which can be served by centralized plants or distributed units, such as CHP systems, heat pumps, geothermal and solar thermal units, heat from waste-to-energy plants or from industry thermal energy surplus. The use of thermal storage solutions allows solar sources to be closely integrated and can be useful for combining different heat sources in the network [110].

There is a long history of research and applications into district heating networks, especially in Baltic and Nordic countries where DH supplies more than 60% of the total, while more than 21% of Austrian households are heated by DH systems. Karner et al. [18] provide an overview of the possible synergies between industries and nearby towns, considering that excess industrial energy can cover a part of the energy demand of the urban area. They include in the industrial energy available for urban recovery typical industrial heat and waste streams (both high temperature and under-90°C waste heat, warm wastewater, and waste), and introduce the exploitation of industrial empty roof space, in which photovoltaic plants for renewable power generation can be installed, as summarized in Table 4.

Energy carrier	Usage	Technology	Temperature range
Waste heat	Heat, electricity, cooling	Heat pump (heating, cooling)	< 90 °C
		Heat exchanger	> 90°C
		Rankine cycle	> 90°C
Wastewater	Heat	Heat pump	35-90°C
		Heat exchanger	> 90°C
Waste	Heat, electricity	Heating plant	> 90°C
		CHP, Rankine cycle	> 90°C
Roof areas	Electricity	Photovoltaic	

	Heat	Solar thermal	< 200°C

Table 4. Possible energy carriers and usage in a urban-industrial context [18].

The model developed for industrial energy usage in urban contexts, which was applied to four urban regions in Austria, shows that up to 35% of the total urban energy demand, and 6 to 46% of the electricity demand, could be supplied by industrial energy thus lowering CO_2 emissions. By analysing the economic viability of integrating industrial energy into urban energy systems in these urban areas [111], different business models for financing and operating plants providing industrial energy can be distinguished, as detailed in Table 5.

Industrial energy	**Financed by**	**Operated by**	**Annual revenues**	**Notes**
Electricity: on-roof PV plant	The company itself	The company itself	Feed-in of total electricity production (feed-in tariffs)	Rather unlikely as the capital commitment and the amortization time are too long
			Feed-in of excess electricity production (feed-in tariffs; relevant for small industrial units and high electricity prices)	
	External company	External company	Green certificates	The company roof is rented
	Citizens participation	External company	Feed in tariffs	The company roof is rented
	Partly by crowdfunding (equity) and the remaining share through banks	External company	Feed in tariffs	Higher interest rate of the publicly financed equity
Heat: delivered	The company	The company		Rather unlikely since the capital

through DH-grid	itself	itself		commitment and the amortization time are too long
	A service company	A service company		

Table 5. Business models for industrial energy project implementation, as in [111].

It should be noted that both the installation and operating phases of power generation plants are not part of the main businesses of companies, so the preferred option is to rely upon external service providers. Based on the different scenarios and as profits for industrial companies and energy service providers must be guaranteed, it was found that the usage of industrial heat is economically feasible in any scenario, while the industrial electricity generated from roof-top PV is only profitable if feed-in tariffs are received, and is significantly influenced by the cost of PV modules. A threshold value determines the profitability of building a waste incineration plant.

A smart energy system approach is suggested by Lund et al. [86], in which smart electricity, thermal energy and gas grids are combined with storage technologies and coordinated, providing synergies among different sectors (industrial, commercial and residential) to achieve optimal sustainable solutions for each individual sector and for the whole system. The benefits for the local communities can be evaluated in relation to environmental restoration and improved well-being, while eco-efficiency and eco-innovation are the main advantages for the involved industries [41]. A regional multi-energy “prosumers” (both energy producers and consumers) scheme based on interconnected energy hubs combining distributed energy supply, RES and CHP, are modelled in [100] to serve residential, commercial and industrial districts.

Afshari et al. [112] propose a mathematical model to extend industrial energy symbiosis to residential areas. In the analysed energy networks scheme, industries share their waste and unused energy with partners, i.e., electricity suppliers, and both industrial and residential energy users. The model determines the potential synergies by minimizing the total cost and environmental impact of an energy exchanger network. It also evaluates the effects of uncertainties on the symbioses over the long term, such as variations in energy demand and supply and in price and considers the concerns of residential and industrial users in the decision-making process. The example shows that improved cost savings and pollution reduction of optimal networks can be obtained by industrial-residential symbiosis compared to industrial symbiosis. The involvement of urban residents in the feasibility study and in the implementation and operation phases of the urban-industrial symbiosis is suggested. A strong interaction between the urban residents and the business park is considered a characteristic of a mixed-use ecopark [113], highlighting the need for a collective awareness and effort in implementing sustainable strategies.

As emerging smart technologies support the transition to low-carbon lifestyles and business patterns, more integrated smart infrastructures and energy management platforms between smart cities and industrial parks will promote the use of renewable energy and urban industrial symbiosis [114].

5. Conceptual framework and a research agenda

The aim of this article is to provide a conceptual synthesis of collective energy strategies and the integration of EIPs and RES, and to design a future research agenda. The importance of developing collective energy strategies has been demonstrated by many authors, who suggest options highlighting the role of EIP and the use of RES at both industrial and urban levels. The review includes a discussion and descriptions of the possibilities, options, and existing solutions for collective energy strategies. Fig. 9 shows the conceptualization framework constructed for the articles retrieved from the literature.

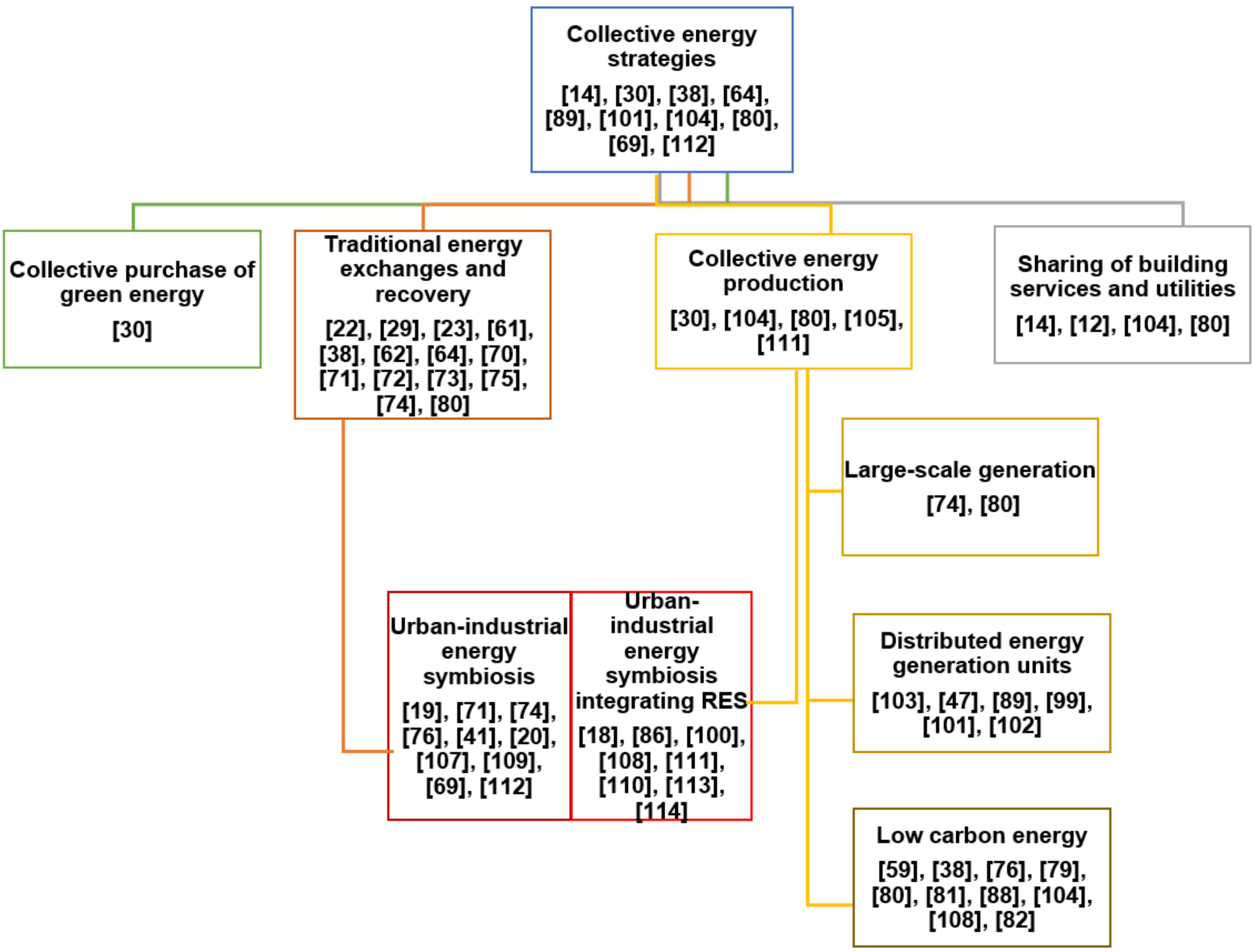

Fig. 9. Conceptual framework and articles focusing on each key element.

Fig. 9 presents articles that support each key element. The scheme emphasizes four main pathways to implement collective energy strategies within an EIP: the collective purchase of green energy, traditional energy exchanges and recovery, the collective production management of energy, and shared building services and utilities.

Collective purchase of green energy covers joint contracting of electricity produced from renewable sources. Traditional energy exchanges and recovery include the use of surplus energy, such as heat exchanges between processes or exchanges via a central utility system, and also involve heat exchangers and intermediate fluids. This category includes waste/sludge treatment facilities for energy production. The term traditional refers to the classical approach to IS. Collective energy production covers collective large-scale plants for the production of clean energy, generating both electrical and thermal energy, and distributed multi-generation units. Both possibilities rely on the integration of low carbon energy (including CHP units and CCS solutions) and the extensive use of RES. Sharing of building services and utilities covers RES integration (e.g., BPIV) for solutions following a nearly Zero-Energy Buildings approach. A wider energy strategy can include energy exchanges between industrial and urban areas, thus developing urban-industrial energy symbiosis.

The conceptual framework developed in this review supports the design of a research agenda for a collective energy strategy to promote RES uptake at the industrial and urban levels.
Some of the key elements identified do not consider the use of RES (traditional energy exchanges and recovery) or would need a specific in-depth analysis to suggest further research opportunities (such as the sharing of building services and utilities).
Future research could include:
(a) simulations for collective energy strategies: while the reduction in GHG emissions as a result of energy symbiosis has been widely demonstrated, we found a few analyses that demonstrate the applicability of such strategies, which can provide technical evaluation tools and raise the awareness of the actors involved in EIP development;
(b) surveys for collective energy production: our review focused on the energy strategies implemented in EIPs. A survey on collective energy production strategies, involving low carbon technologies, would facilitate generalization of the study results for the initial design of EIP development schemes;
(c) case studies and subsequent action research for distributed energy systems in EIPs, to obtain results from the application of qualitative and quantitative modelling and evaluation of different technological and organizational strategies. Although in the reviewed papers, the energy exchanges (mainly heat) within EIPs have been extensively modelled and studied, few papers apply the distributed energy systems scheme to EIPs and only one case study have been found [102]. EIPs represent a suitable platform for modelling and testing multi energy systems.
(d) there is a wide research gap in terms of integrating RES in urban-industrial energy symbiosis: the advantages of energy symbiosis networks between industrial and urban areas that also integrate renewable energy systems is still under-investigated. RES integration through distributed

architectures, often separately analysed in terms of EIPs and at the community level (urban areas) [115], also needs further investigations. In this context, energy management plays a critical role in overall efficiency improvements as well as in CO_2 emission reduction [116,117] Therefore, energy efficiency management in energy-intensive industries [118,119] as well as machine-learning techniques for energy management [120,121] can also be studied in in-depth case studies, associated with RES networks.

6. Conclusions

The industry sector is urged to reduce carbon emissions by materials and energy efficiency measures. Replacing fossil fuels with renewable energy sources would help to reduce carbon emissions at the industrial level. However, individual firms prioritise value-adding processes over energy related projects that require specific expertise, which is often not available internally. Cooperation in industrial parks can help overcome the lack of technical knowledge regarding low carbon and renewable technologies at a reasonable cost, by collectively consulting a service provider. Eco-industrial parks, which were set up to reduce the environmental footprint of the firms involved, represent a suitable cooperative model for fostering the integration of RES in the industrial system.

The paper presents the results of a literature review that has explored the synergetic possibilities of integrating EIP and RES, enabling the uptake of renewable energy sources at an industrial level and potentially creating urban-industrial energy symbiosis.

Three main themes emerged from the reviewed papers: i) the sustainability of energy projects within EIPs; ii) energy symbiosis schemes within EIPs promoting RES integration; and iii) urban-industrial energy symbiosis.

We believe that this review contributes to the literature by providing an original perspective on the sustainability potential of EIPs focused on energy symbiosis. We have organized knowledge on energy sustainability in industrial parks within a conceptual framework. This framework demonstrates viable solutions and the effectiveness of RES integration within EIPs for reducing the carbon footprint of industry, and potentially creating urban-industrial energy symbiosis.

This study involved a review and analysis of papers on energy symbiosis strategies within eco-industrial parks, both considering the influence of EIP models on energy issues and the use of renewable energy sources. In addition, it reviews and analyses the urban-industrial energy symbiosis approaches originating from EIP energy management solutions which include RES.

The possibilities, options, and existing solutions for collective energy strategies within EIPs were analysed, and a conceptualization framework was presented, which shows four main pathways for creating collective energy strategies. In addition to the classical IS approach consisting of inter-firm energy exchanges, the collective purchase of green energy, the collective production management of energy, and shared building services and utilities are viable solutions for improving RES uptake at the industrial level.

The study has resulted in a conceptualization framework demonstrating four main pathways to implement energy synergies within EIPs and viable solutions to improve the uptake of renewable energy sources at the industrial level. The conceptual framework supports the design of a future research agenda by revealing the most promising research opportunities as key elements. The main gap identified in the research is that the advantages of energy symbiosis networks between industrial and urban areas that also integrate renewable energy systems have not been fully investigated.

We believe that this paper provides researchers, technicians, industry managers and decision makers involved in energy managing and sustainability issues, with an outlook of the implemented and possible options to promote GHG mitigation in the industry sector with the aim of both informing and providing suggestions for further studies.

The key points of this review are:

o An analysis of energy symbiosis schemes within eco-industrial parks, considering the influence of EIP models on energy concerns and the use of renewable energy sources as viable options to reduce industry GHG emissions

o An analysis urban-industrial energy symbiosis approaches originating from EIP energy management solutions that include renewable energy sources

o A conceptual synthesis, showing four main pathways for creating suitable collective energy strategies aimed at improving RES uptake at the industrial level

o Several future research opportunities, revealing that the advantages of energy symbiosis networks between industrial and nearby urban areas that also integrate renewable energy systems are still under-investigated.

The main limitation of the research is due to the spreading of research field related to the topic under study. The study thus represents a first synthesis of the knowledge in the fields of energy symbiosis, eco-industrial parks and renewable energy sources. A more in-depth analysis of the literature should be performed on more specifically energy-related themes which can support the implementation of energy symbiosis schemes involving RES. Future studies could review the methods for energy analysis and optimization, analysing the suitability for energy strategies within EIPs and in urban-industrial energy symbiosis projects. Applying these methodologies to case studies would also be valuable.

As previously mentioned, the main challenges identified by this study require future experimental research, in terms of applying the collective energy strategies to specific case studies.

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