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Ciclo XXXIII

# Local energy systems integrating renewable energy sources: state-of-the-art and innovative solutions in the framework of industrial symbiosis and urban-industrial symbiosis

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## SOMMARIO

La riduzione delle emissioni climalteranti è considerata un obiettivo strategico, sia a livello europeo che globale. Una maggiore diffusione delle fonti energetiche rinnovabili (FER) è considerata essenziale per una transizione verso un sistema energetico più sostenibile. Questa transizione verso un'energia a basse emissioni di carbonio richiede lo sviluppo e l'uso di tecnologie innovative, in particolare nei settori di utilizzo finale (edifici, industria e trasporti), e nuovi approcci economici, di gestione e di mercato.

Lo studio presentato in questa tesi esplora le opportunità sostenibili offerte dall'approccio di simbiosi industriale e urbano-industriale basati sull'energia. La simbiosi industriale energetica (SIE) propone la condivisione di risorse, strutture e infrastrutture legate all'energia come un modello efficace per promuovere misure di risparmio energetico e l'adozione di fonti energetiche rinnovabili a livello industriale. Inoltre, è possibile perseguire una strategia energetica a basse emissioni di carbonio creando sinergie energetiche tra i distretti industriali e le aree urbane adiacenti. Stabilire la simbiosi energetica urbana-industriale (SUIE) consente di ottimizzare la produzione e il consumo di energia e di sfruttare il know-how locale e le risorse umane. Il nuovo sistema integrato necessita infatti di un cambio di prospettiva, considerando un'azione multi-stakeholder: aziende di servizi energetici, comunità locali, settore industriale, consumatori, policy maker, ricercatori devono impegnarsi attivamente nei processi di pianificazione partecipativa per guidare la trasformazione del sistema energetico e del processo di ricerca e innovazione, e rispondere adeguatamente alle esigenze del territorio.

Nella tesi viene presentata un'analisi approfondita dei molteplici driver e barriere tecnici, economici, organizzativi, normativi, ambientali e sociali dell'approccio di simbiosi energetica, con l'obiettivo di modellare le configurazioni ottimali delle sinergie energetiche tra le imprese che comprendano l'uso di FER. Viene inoltre sviluppata una metodologia per supportare energy manager, singole imprese, gruppi di imprese all'interno di parchi industriali e decisori per valutare le sinergie e i progetti energetici che coinvolgono FER, tenendo conto degli impatti economici, ambientali e sociali dei progetti.

Inoltre, viene sviluppato un framework orientato alla sostenibilità con l'obiettivo di modellare le sinergie energetiche urbano-industriali comprendenti le FER da un punto di vista multi-stakeholder per supportare il processo decisionale sulla sostenibilità economica, ambientale e sociale delle sinergie energetiche.

L'applicazione degli strumenti decisionali sviluppati a specifici casi studio consente di sottolineare come le strategie collettive (SIE o SUIE) consentano una migliore gestione della fornitura di energia da fonti rinnovabili.

## ABSTRACT

Reducing emissions responsible for the climate change is recognized as a strategic goal at European and global level. A higher deployment of renewable energy sources (RES) is considered as essential for a transition towards a more sustainable energy system. This low-carbon energy transition requires both the development and use of innovative technologies, particularly at end-use sectors (buildings, industry and transport), and new management approaches as well as new market design and business models.

This study explores the sustainability driven opportunities offered by the energy based industrial symbiosis and urban-industrial symbiosis approach. The industrial energy symbiosis (IES) considers the sharing of energy-related resources, facilities and infrastructures as an effective model to promote energy conservation measures and the renewable energy sources uptake at the industrial level. In addition, an improved low-carbon strategy can be achieved creating energy synergies between industrial districts and the adjacent urban areas. Establishing urban-industrial energy symbiosis (UIES) allows optimizing the energy production and consumption and exploiting the local knowhow and human resources. These new integrated system needs a change of perspective, considering a multi-stakeholder action: energy service companies, local communities, industry sector, consumers, policy makers, researchers must get actively involved in participatory planning processes to guide the transformation of the energy system and the research and innovation process, and respond adequately to the needs of the territory.

Thus, an in-depth analysis of the manifold technical, economic, organizational, regulatory, environmental and social drivers and barriers of the energy symbiosis approach are presented, with the aim of modelling the optimal energy synergies configurations among firms including RES. A methodology is developed to support energy managers, single firms, groups of firms within industrial parks, and decision-makers to evaluate energy synergies and projects involving RES, taking into account the economic, environmental and social impacts of the projects.

Lastly, a sustainability-driven framework is developed, with the aim of modeling Urban–Industrial energy symbiosis networks integrating RES from a multi-stakeholder point of view and supporting decision-making on the economic, environmental, and social sustainability of the energy synergies.

The application of the developed decision-making support tools to specific case studies emphasizes how collective strategies (IES or UIES) allow better management of the energy supplied by renewable sources.

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# INTRODUCTION

The low carbon transition of the energy system is widely considered the main pathway to mitigate the climate change.
This transition requires a multi-faceted effort, including a higher deployment of renewable energy sources (RES), the development of innovative technologies to be employed both at the energy conversion level and at the end-use sectors (building, industry and transport), more effective energy and resources management approaches, new market design and new business models.

Industry is one of the main sector contributing to energy demand and is responsible for one-fifth of global energy related $CO_2$ emissions, so the need for reducing the industry carbon emission and improving the sustainability of industrial areas is recognized at academic, policy and practitioners' level. At industry level the objective of reducing GHG emissions can be achieved through the promotion of equipment and processes efficiency and energy savings, and the use of energy from RES. Many renewable energy technologies are available for industrial applications, however, single firms may be reluctant in investing both in energy efficiency solutions and RES, due to techno-economic factors and lack of expertise in the field of energy, that is not the main business they manage.

A suitable framework for improving the sustainability of industry and foster the uptake of renewable energy at industry level is represented by the industrial symbiosis (IS) approach. Within this framework, separate companies establish cooperative synergies between each other, involving the collective management and the exchange of resource flows (materials, water, and energy) and by-products. An industrial area is naturally suited to foster cooperation and resource-sharing among businesses, thanks to geographical proximity. So, the eco-industrial parks (EIPs), comprising a community of businesses connected by collaborative relationships, can be considered an application of the IS approach to industrial systems. The EIPs include 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.

The purpose of this thesis is to explore the opportunities that the IS approach provides to industrial areas and neighbor territory of reducing their carbon footprint, to model advantageous and sustainable energy synergies configurations including RES.

The study proceeds through a cross-cutting approach to clean energy innovation, integrating three main research fields in a sustainability perspective: the industrial ecology body of knowledge, with a focus on the industrial symbiosis, the distributed energy configuration integrating RES and the sustainability of energy projects.

In this research context, the energy-based industrial symbiosis shows a great potential for reducing industry carbon footprint. But, while thermal energy exchanges have been widely analysed, only few studies consider the RES integration and the electricity production and exchanges. Thus, a new mathematical model is presented, with the aim of analysing the integration of RES in the energy system of an EIP and supporting energy managers, single firm or a group of firms within EIPs and, in general, decision makers to evaluate the realization of energy synergies and projects involving RES within EIPs. The application of the model demonstrates that if enterprises implement a collective energy strategy, they can achieve a sum of benefits higher than acting individually.

The study is then extended to the urban-industrial symbiosis, and a local project for implementing resources exchanges and low-carbon energy links between an industrial park and the neighbor urban area is designed.

The structure of the thesis is as follow.

In the first chapter a literature overview presents the IS approach, both from the theoretical and practical point of view, including the analysis of the eco-industrial parks structure and sustainability aspects. Then, the main renewable technologies appropriate for industrial applications are presented. This chapter provides the general context of the research.

The second chapter focuses on the energy-based IS within EIPs. The modelling methods of EIPs, energy exchanges, and multi-energy systems including RES are reviewed, to support the modelling of energy symbiosis exchanges integrating RES within EIPs. Lastly, the sustainability issues of such a model are analysed and a suitable sustainability criteria system presented.

The third chapter includes the development of the model for renewable energy symbiosis networks in EIPs, with some applications.

Lastly, the fourth chapter focuses on the main UIS approaches involving low-carbon energy links between industries and cities, aiming at investigating the potential of creating RES synergies at urban-industrial level. A project for the implementation of an energy-based urban industrial symbiosis is designed and presented.

# *Chapter 1*
# Low carbon energy transition of industry within the framework of Industrial Symbiosis

According to IRENA (IRENA, 2018), the global industry sector accounts for almost 40% of final energy demand and is responsible for one-fifth of global energy related $CO_2$ emissions. Reducing the negative environmental impacts of industries is a major challenge, both in advanced and emerging economies: if 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 (Johnson *et al.*, 2017), the quality of air is worsening in rapidly growing economies, as industrial clusters bring about both economic growth and environmental impacts (Gereffi and Lee, 2016).
A great effort is devoted to find the diverse and effective solutions needed for reducing the carbon footprint of the industry sector, considering technological and policy issues (Rissman *et al.*, 2020). Considering the energy-related emissions, solutions to improve the efficiency of equipment and processes, the replacement of fossil fuel with renewable energy sources (RES), and electrification are among the most known technology options to reduce industrial emissions. One less employed solution is energy cascading, i.e. considering the reuse of waste heat resulting from a process into another process or for general heating (Wiese and Baldini, 2018).

This chapter presents an overview of the industrial symbiosis approach, that provides a suitable framework for improving the sustainability of industry, mainly within the eco-industrial parks, industrial areas naturally suited to foster cooperation and resource-sharing among businesses. Then, the main renewable technologies appropriate for industrial applications are presented.

This chapter is partially based on the papers:

-*Renewable energy in eco-industrial parks and urban-industrial symbiosis: A literature review and a conceptual synthesis,* published in 2019 in the Journal Applied Energy, vol. 255, 113825, doi: 10.1016/j.apenergy.2019.113825.

- *Barriers, drivers, and relationships in industrial symbiosis of a network of Brazilian manufacturing companies*, published in 2021 in the Journal Sustainable Production and Consumption, vol. 26, pp 443-454, doi: 10.1016/j.spc.2020.09.016.

# 1 THE INDUSTRIAL SYMBIOSIS

The concept of industrial symbiosis (IS) arised establishing similarities between the biological ecosystem and the "industrial ecosystem", proposed since the late 1980s (Frosch and Gallopoulos, 1989) to introduce a pathway to a sustainable industrial development. In both systems a transformation of energy and matter takes place. But, while the biological system is self-sustaining, in the traditional model of manufacturing industry the companies consume raw materials to generate products to be sold and produce waste to be disposed, as if they were entities disconnected from the context in which they operate. This linear production model is not sustainable.

Various authors therefore propose a change of perspective, which considers an integrated model of consumption and transformation, just like biological ecosystems. Thus the paradigm of "industrial ecology"[1] is introduced, providing for the the design of industrial systems aiming at reducing their impact on the environment by closing energy and resource loops.

The concept of industrial symbiosis, has evolved through the academic debate (Chertow, 2000; Chertow and Ehrenfeld, 2012; Lombardi and Laybourn, 2012) and specific projects (Chertow, 2007; Chertow and Park, 2015). It represents an effective approach to sustainability in the industry sector. The IS is considered a part of the industrial ecology field of knowledge as it focuses on the optimization of the materials cycle and fulfills the circular economy principles of reusing, recycling and remanufacturing materials thereby increasing resource efficiency, reducing waste and pollution, and bringing about economic benefits (Baldassarre *et al.*, 2019; Domenech and Bahn-Walkowiak, 2019).

Within the framework of IS the consumption of materials and energy is optimized, and the production of waste is minimised looking for the opportunity of reusing by-products and process waste as raw materials for other processes, within the same company or by creating collaborations with neighboring companies. IS deals precisely with the realization of these exchanges of materials, water, energy, services and by extension of knowledge, with a view to “green” innovation.

Many IS interpretations are given in literature. One of the first definition of the IS concept, and the most cited, is that of Chertow (Chertow, 2000): IS engages “*traditionally separate industries in a collective approach to competitive advantage involving physical exchange of materials, energy, water, and by-products. The keys to industrial symbiosis are collaboration and the synergistic possibilities offered by geographic proximity*”. The geographic proximity allows the use of local infrastructure, the sharing of regulatory system, the reduction of logistics cost and the possible existing social relationship with neighbour firms; the establishment of regional symbiosis coordination can foster the widening of the useful distances (Jensen *et al.*, 2011). Exchanges along a supply chain (depending also by the type and value of the waste stream) or among different departments of a same large company, can make synergies and exchanges advantageous over long distances (Sellitto *et al.*, 2021).

(Lombardi and Laybourn, 2012), in their is definition, suggest a paradigm shift, emphasizing the innovation-related aspects of IS: “*Industrial symbiosis engages diverse organisations in a network to foster eco-innovation and long-term culture change. Creating and sharing knowledge through the network yields mutually profitable transactions for novel sourcing of required inputs, value-added destinations for non-product outputs, and improved business and technical processes*”. (Diemer, 2017) observes that IS should be based on four pillars: eco-efficiency (associated with industrial metabolism, i.e. the input-output mechanism), cooperation (more than competition), resilience, and proximity (considering the whole territory and a comprehensive sustainability view that includes the social aspects).

[1] VVAA, Taking Stock of Industrial Ecology, 2016, Springer Open, DOI 10.1007/978-3-319-20571-7

## 1.1 DRIVERS AND BARRIERS TO IS

IS activity assessments demontrated that waste reduction and grenhouse gas (GHG) emissions reduction are the main environmental benefits, associated with economic benefits, mainly due to costs reduction and new revenue streams, and social benefits due to jobs creation. These advantages are also the main drivers for the emergence of IS. While one of the main barrier is the reluctance to provide the quantitative information regarding the processes and waste generation needed for evaluating, planning and implementing the exchanges (Neves *et al.*, 2020a). A summary of drivers and barriers to IS as collected in literature is presented in the next Table 1 (the complete table is available in (Sellitto *et al.*, 2021)).

| **Barriers/ Hindering Factors** | **Description** |
|---|---|
| Processing cost | Cost to fully process a by-product unit |
| Logistics cost | Cost of storage and transportation of a by-product unit |
| Risk of discontinuity | By-products provided by erratic or intermittent operation does not assure continuity in the supply |
| Excessive availability/ Lack of availability | An imbalance between generation and consumption of a by-product jeopardizes the relationship |
| Lack of research | Companies/managers do not know how to reuse by-products |
| Lack of awareness | Companies are not informed on existing opportunities for reuse by-products |
| Lack of legal requirements | Companies are not capable to comply with or are unaware of legal requirements |
| Stringent legislation | Local legislation may require time-consumption and/ or cost-increasing procedures that make exchange unfeasible |
| Inter-companies cooperation | Companies refuse to cooperate due to strategic reasons |
| **Drivers/Stimulating factors** | |
| Cost reduction | Companies achieve a competitive edge by cost reduction due to reuse |
| New revenue | Companies achieve a competitive edge by cost reduction due to reuse |
| Increase the life of deposits and controlled landfills | Reuse of by-products reduce the rate of extraction of existing deposits and at the same time reduce the rate of dumping to landfills |
| Support a new product or brand | By-products may aggregate features to existing products, turning them into a new product |
| Support a new business | By-products may allow launching a new company devoted to reuse it |
| Compliance with legal requirements | Companies avoid fines and other kinds of penalties |
| Reduction of landfill saturation | Besides increasing the useful life of landfills, reduced rates of dumping decrease saturation and gives more time to natural soil recovery |
| Resource scarcity | Reuse postpones shortage of scarce raw materials, giving time to find a replacement |
| Financial benefits | Companies can grant subsidies and other financial incentives to reuse by-products |
| Inter-companies competition | The achievement of a competitive edge can drive companies to reuse by-products |

*Table 1. Summary of barriers and drivers to IS collected in literature.*

Walls and Paquin (2015) distinguished the factors that, according to the papers they analysed, facilitates the creation of industrial symbiosis (*antecedents*), help IS to grow over time (*lubricants*) or inhibit IS to grow over time (*limiters*), and the outcomes of IS (*consequences*) (Figure 1).

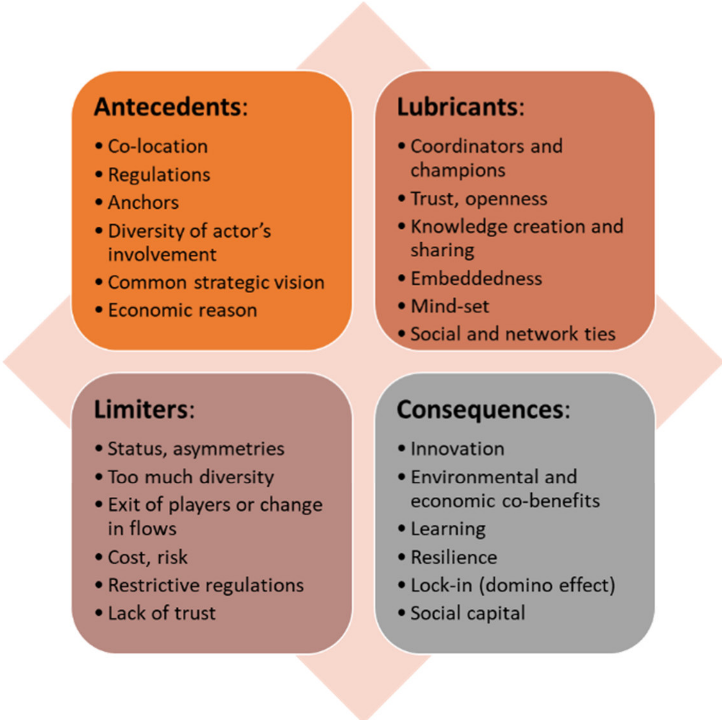


*Figure 1. Factors influencing IS according to Walls and Paquin (2015).*

Three main phases in the IS emergence process are identified by (Mortensen and Kørnøv, 2019):

- awareness and interest in IS,
- reaching out and exploration of connections, and
- organizing.

In all the three phases the research and education institutions are considered key stakeholders, supporting activities of knowledge sharing and development, and providing technical support to innovate, together with local or governmental bodies that can provide incentives and support to companies, acting as facilitators. Other actors and stakeholders are the companies, associations, consultancy companies, technical and service providers, local administrations and institutions, and the local communities.

## 1.2 Governance models

(Fraccascia, Giannoccaro and Albino, 2019) schematise the governance models according to the levels of coordination and centralization (Figure 2).

The depicted business models go from low coordination-low centralization, as in the case of large companies implementing internal exchanges, to high coordination-high centralization, as in the case of multiple exchanges between independent companies, coordinated by a central entity.

High coordination-low centralization includes peer-to-peer inter-firm exchanges, while in low coordination-high centralization a central entity, e.g. a local multi-utility, implements exchanges with single firms (or collected resources from them).

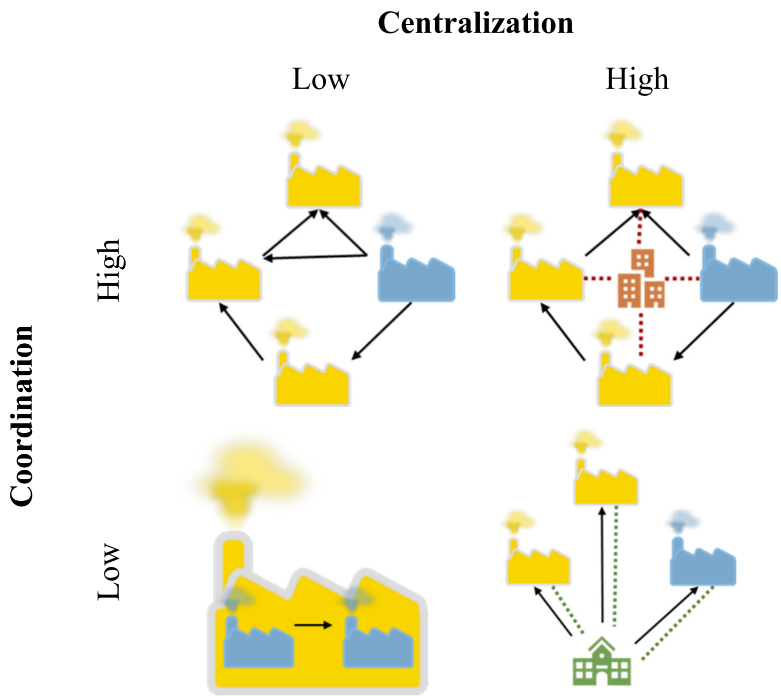


*Figure 2. IS business models (adapted from (Fraccascia, Giannoccaro and Albino, 2019))*

## 1.3 Industrial Symbiosis assessment

The main evaluated impacts of IS are the environmental ones, followed by the economic ones (Fraccascia and Giannoccaro, 2020). The reduction in the environmental impacts can be evaluated both from the upstream perspective, measuring the reduction in the amounts of materials, energy, and water used as inputs by industrial processes, and from the downstream perspective, measuring the reduction in the amounts of wastes discharged in landfill, wastewater discharged, waste energy not exploited, and GHG emissions.

The measurements methodology applied to the evaluation of IS can be classified into four groups:

- flow analysis (Material Flow Analysis, Substance Flow Analysis, and Enterprise Input-Output approach);
- thermodynamics (emergy analysis and exergy analysis);
- LCA (Life cycle assessment, that can be applied to three different spatial levels: single company, single IS relationship, and IS network);
- network analysis (four methodologies related to this approach have been used in the IS field: social network analysis, stakeholder value network approach, ecological network analysis, and food web analysis.).

Regarding the economic dimension, three types of indicators are measured:

- cost savings, that is the reduction in the waste disposal costs and input purchasing costs;
- economic value created by IS, that, in addition to cost savings, includes: the operational costs (waste transportation, waste treatment, transaction costs of IS cooperation); the additional costs or revenues coming from selling/buying wastes to/from the symbiotic partner(s), the additional gains generated by selling new products generated thanks to using wastes, etc.;
- comprehensive economic feasibility of IS synergies, that considers the cash flow generated by the investment in IS.

## 1.4 POLICY

From the policy point of view, the European Union supports IS approach since the revised CE package launched in 2015; within the framework of the European Green Deal, the New Circular Economy Action Plan[2] (2020) foresees the launch of an industry-led industrial symbiosis reporting and certification system. (Domenech *et al.*, 2019) reported an overall updated overview of IS activity in Europe, identifying at least 70 IS networks of different typologies (self-organized, facilitated and planned) and differently sized, located in many of the EU Countries. Many EU funded projects implementing IS approaches are ongoing or recently closed: among others, MAESTRI, Sharebox and EPOS, funded under the H2020 EU Framework Programme, and TRIS and SYMBI, funded under the Interreg Europe ERDF Programme.

The European Committee for Standardization (CEN) released its Workshop Agreement CWA-17354:2018[3], aiming at supporting the mainstream adoption of good practice approaches proven through implementation by advancing the mutual understanding of actors (public, private, third sector, and community) currently using the term industrial symbiosis in different ways. Here, the following definition of IS is given: "*Industrial symbiosis is the use by one company or sector of underutilised resources broadly defined (including waste, by products, residues, energy, water, logistics, capacity, expertise, equipment and materials) from another, with the result of keeping resources in productive use for longer. It presents a systems approach to a more sustainable and integrated industrial economy that identifies business opportunities to improve resource utilisation and productivity*".

Other national programs or policies have supported IS approach, such as Japanese Eco-Town project (Van Berkel, Fujita, Hashimoto and Geng, 2009), Korean (Park, Park and Park, 2016) and Chinese (Shi, Tian and Chen, 2012) National programs, NISP program in UK[4], US and Canada (Neves *et al.*, 2019). An extensive literature on IS case studies is available (Neves *et al.*, 2020a), showing a widespread geographic distribution of IS projects, characterized by diverse participating economic activities. The mix of industry sector mainly depends on the economic reality of each country, but, as a general trend, manufacturing industries are the most present probably due to the volume of waste they generate together with their greater opportunities of using both waste and by-products as new raw materials. Within this industry type, the most frequent industry sectors present in the IS projects are the chemical, cement, pulp and paper, and steel and iron industries and refineries, sectors characterized by high energy consumption and so motivated in finding measures to reduce the negative impacts of their processes.

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[2] https://ec.europa.eu/environment/circular-economy/pdf/new_circular_economy_action_plan.pdf

[3] https://standards.cen.eu/dyn/www/f?p=204:110:0::::FSP_PROJECT,FSP_ORG_ID:68554,2412012&cs=182838A4EB956A5BA5EA563CB6AD47C73

[4] https://ec.europa.eu/environment/waste/prevention/pdf/NISP_Factsheet.pdf

# 2 SUSTAINABLE INDUSTRIAL SITES: THE ECO-INDUSTRIAL PARKS

The need to improve the sustainability of industrial sites[5] has become a priority to face climate change issues and to reduce the environmental impact of industry at the local and global level. In order to meet the Sustainable Development Goals (SDG) set by UN and the objectives of the 2030 Agenda, the economic growth should be decoupled from resource consumption, allowing to meet wider social objectives (UNIDO, 2019).

The eco-industrial park (EIP) is the sustainability driven evolution of the conventional industrial park: it can be considered a middle-level application of the industrial symbiosis approach, that can range from the single-plant level to the macro-level of regional clusters or global network of companies (Figure 3).

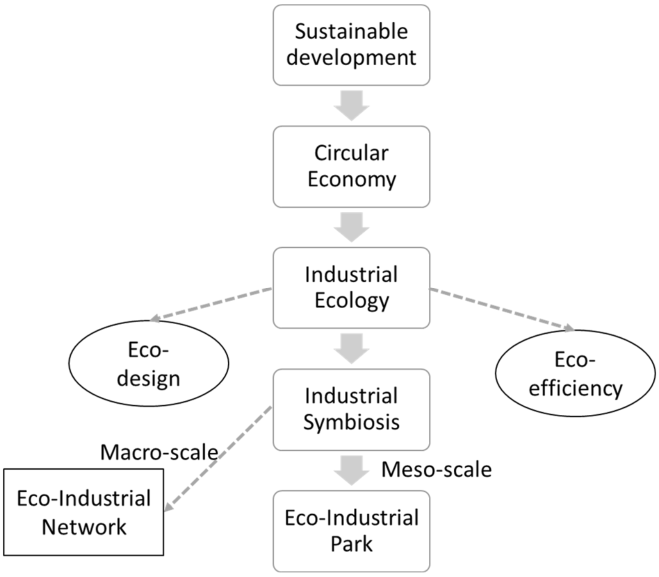


*Figure 3. EIP concept positioning within the sustainable development framework (adapted from (Le Tellier et al., 2019)).*

EIPs comprise a community of businesses, mainly located in the same geographical area, naturally suited to foster cooperation and resource-sharing. EIPs are modelled as networks of manufacturing and service businesses, sharing the same willingness to efficiently use natural and economic resources, increase the economic performance of the participants, reduce the overall environmental impact and create benefits for local communities.

## 2.1 LITERATURE OVERVIEW

Many EIP's definitions have been given by academic and practitioners from the early '90, each of one underlying one or more of the priorities that characterize the inter-firm synergies on which the clustering is based, but, as is the case of industrial ecology, the definition of an eco-industrial park is still evolving following technology innovations, developed theoretical frameworks and the regional or national programs supporting EIP or industrial symbiosis initiatives.

(Lambert and Boons, 2002) compare two definitions, very similar but with different focus: the first focuses on societal performance (organizational and societal processes) while the second emphasizes technical performance (materials and energy physical flows):

[5] In this thesis, industrial sites, districts, clusters or zones (or business parks) are used as synonymous of industrial parks, and intended as areas where a number of industrial activities are co-located, sharing infrastructure and commonalities, with the objective of fostering economic growth and improving a location's competitiveness; the difference among the different labeling due to the academic use, the local regulations or linguistic nuances are marginal respect to the scope of the present study.

1. *A community of businesses that collaborate with each other and with the local community to efficiently share resources (information, materials, water, energy, infrastructure and natural habitat), leading to economic gains, gains in environmental quality, and equitable enhancement of human resources for the business and local community*.

2. *An industrial system of planned materials and energy exchanges that seeks to minimise energy and raw materials use, minimise waste, and build sustainable economic, ecological and social relationships*.

More recently, (Lombardi and Laybourn, 2012) observed that the definition of EIPs should include "*the exchange of knowledge, information, and expertise*", as they act as sources of innovation and can improve the type and the number of exchanges.

The UNIDO (United Nations Industrial Development Organization) uses the following definition[6]:

"*A community of manufacturing and service businesses located together on a common property. Member businesses seek enhanced environmental, economic, and social performance through collaboration in managing environmental and resource issues*"

where the focus is clearly on the sustainability driven objectives of the clustering.

Lastly, many definitions (see for example (Martin, Weitz and Cushman, 1996)) underlines as "*By working together, the community of businesses seeks a collective benefit that is greater than the sum of the individual benefits each company would realize if it optimised its individual performance only*".

Apart from the possible or given definitions, the features that EIPs should include are (Daddi, Tessitore and Testa, 2015; Bellantuono, Carbonara and Pontrandolfo, 2017; Liu *et al.*, 2018; Le Tellier *et al.*, 2019):

- taking advantage of geographical proximity;
- clustering firms that are complementary in terms of economy;
- integrating ecological capacity into planning decisions;
- maximizing the use of renewable energy;
- green buildings design;
- material redundancy within the structure of the system - closing material cycles through the use of waste materials;
- water and wastewater infrastructure to recover and reuse water or utility sharing;
- shared services and technologies;
- information management systems which facilitate networking;
- involvement of local stakeholders.

It is clear from the previous list that beside the exchange of materials (waste, by-products) and energy flows, the possible synergies involve the sharing of infrastructure, equipment, services as well as technical skills and waste collection and treatment. This means that the trust and cooperation between firms must be developed at the beginning of a symbiosis project, and the willingness to share data and information regarding the company needs is a prerequisite for the implementation of onerous technical synergies solutions and long-term cooperation (Belaud *et al.*, 2019). Thus, according to (Martin, Weitz and Cushman, 1996) an EIP can include any of the following characteristics, but it is more than:

- a single by-product exchange pattern or network of exchanges;
- a recycling business cluster (e.g. recycling companies);
- a collection of environmental technology companies;
- a collection of companies making "green" products;

[6] Given by Lowe E.A. (2001). Eco-industrial parks: A handbook. Asian Development Bank, Manila, Philippines.

- an industrial park designed around a single environmental theme (i.e., a solar energy driven park);
- a park with environmentally friendly infrastructure or construction; and
- a mixed use development (i.e., industrial, commercial, and residential).

Three main categories of EIPs can be distinguished from the existing initiative (Lambert and Boons, 2002):

- *Industrial complexes*: geographically concentrated industrial activities, involving mainly process industries, with tight 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 located in dedicated areas.
- *Eco-industrial regions*: referred to as administrative areas where diverse or related industrial enterprises are located (sometimes called *virtual EIPs*).

EIP projects can be developed from spontaneous cooperation initiatives among companies motivated to improve efficiency and cut costs (bottom-up model) or promoted by governmental or other institutional initiatives (top-down model). The EIP projects can be further distinguished between *greenfield*, the establishment of new industrial park, and *brownfield*, referring to the reorganizing of existing industrial parks. Among the reasons that can push an industrial park to convert in EIP, the main are: mitigating climate change and energy security, greening the supply chain, and minimizing operating costs while improving productivity (Kechichian and Jeong, 2016).

More in detail, (Chertow and Ehrenfeld, 2012) identified five types of existing eco-industrial park development models as:

- *Build and Recruit*: New industrial park establishment where compatible industries are searched for participating.
- *Planned EIP*: this model derives from the previous one, adding an oriented effort to identify companies across different industries for inter-company exchanges, often with government support.
- *Self-organizing symbiosis*: the resources exchanges are privately developed among firms, arising from the self-interest of firms aiming at reducing costs.
- *Retrofit of industrial park*: Conversion of existing industrial parks into EIPs, after build and recruit has occurred.
- *Circular economy EIP model*: developed in China, strongly supported by institutional programs, it fosters resource sharing and other environmental opportunities as a means of reducing private costs while creating public environmental benefit.

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 interest of individual actors to participate in initiatives.

The success of EIP initiatives is driven by the profits and environmental benefits. Among major factors that impacts the successfulness of EIP projects, the cost savings and enhanced competitiveness have been identified due to: shared infrastructure costs, improved revenues, access to and development of new technologies with improved opportunity for investment (new businesses), more skilled human resources and job creation (Yedla and Park, 2017).

Accordingly, the main barriers to the establishment of exchange relationships are (Heeres, Vermeulen and de Walle, 2004):

- technical: unfeasibility of the exchange,
- economic: the exchanges can require investments not affordable (or risky)
- informational: if the information does not reach the right persons timely
- organizational: the intended exchange might conflict with the firm organizational structure

- regulatory

## 2.2 SOME CASE STUDIES

The business benefits of existing EIP projects have 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. Direct and indirect economic benefits are recognized for participating companies: direct benefits are due to avoided discharge fee or reduced disposal costs for the reuse of exchanged high value by-products (e.g. steam or water); indirect economic benefits are related to improved operational capability (due to, among others, supply security, increased flexibility, innovation) (Veleva *et al.*, 2015).

(Heeres, Vermeulen and de Walle, 2004) investigate successful EIPs implementation in the USA and in the Netherlands, comparing process and physical factors recognized as drivers for realizing EIPs projects. Interestingly, only some of the drivers identified in the literature (Table 2) as "highly important" for a successful EIP have the same importance in the analysed EIPs, with significant differences between the US and Dutch EIPs, showing a strong dependence by the local/regional conditions, in addition to park size, industry mix in park, community concerns, business opportunities, etc.

| ***Drivers*** | | ***Importance in literature*** |
|---|---|---|
| *Process* | EIP as an environmental project | +++ |
| | EIP as an economic project | +++ |
| | Involvement of local/regional government | ++ |
| | Involvement of national government | ++ |
| | Involvement of local entrepreneurs' association | - |
| | Involvement of local industry | +++ |
| | Community involvement (residential) | +++ |
| | Anchor tenant | +++ |
| | Local champion | +++ |
| *Physical* | Exchange infrastructure for wastes and by-products | +++ |
| | Energy cascading and cogeneration | +++ |
| | Water infrastructure | +++ |
| | Telecommunications infrastructure (site-wide) | +++ |
| | Utility sharing | +++ |

*Table 2. EIPs' process and physical drivers identified in literature by (Heeres, Vermeulen and de Walle, 2004) with the related importance scaled from – to +++.*

From the Table 2 it is evident that beside the drivers related to the technical feasibility, the involvement of the key stakeholders is essential for the EIP projects start. Moreover, as often observed in the literature, an EIP project can be triggered by the presence of an anchor tenant, i.e. a major manufacturer able to provide the EIP with a continuous waste stream that can be potentially used by third parties in their manufacturing processes (sometimes an anchor tenant can also be an incubator), or a local champion, who initiates the process and engages the key stakeholders.

(Bellantuono, Carbonara and Pontrandolfo, 2017) presented a framework to analyse the EIPs main features through two dimensions: organizational, emphasizing the fact that EIPs are clusters of firms, and a sustainability dimension, indicating the environmental and social peculiarities of EIPs. Nine organizational variables describe how EIPs have been developed, how they are managed, which kinds of external cooperation exist, and if shared information systems and infrastructure exist. Eight environmental and four social variables cover the sustainability objectives pursued within the EIPs. The dimensions and variables are listed in Figure 4.

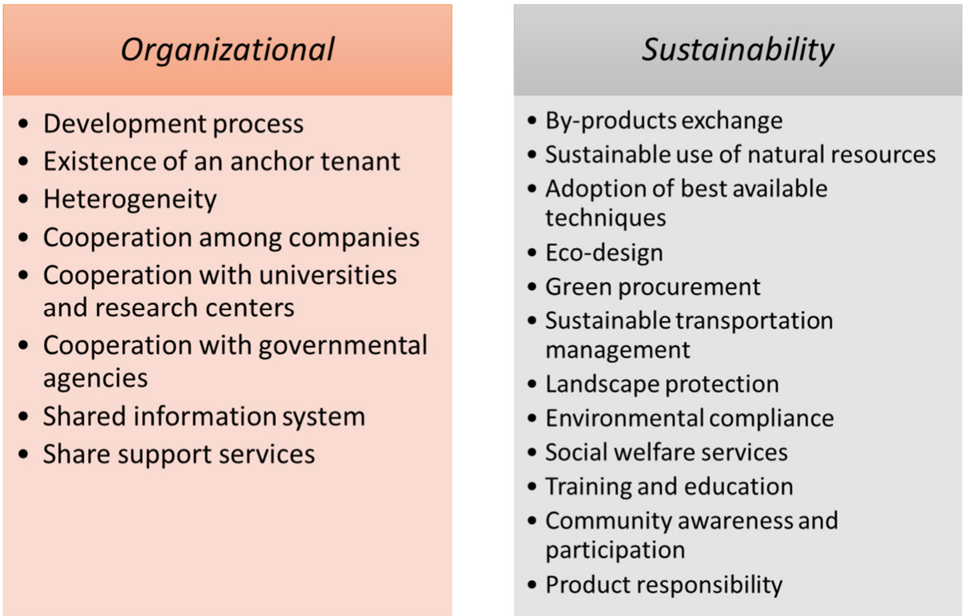


*Figure 4. Dimensions and related variables for assessing the EIPs according to the framework developed in* (Bellantuono, Carbonara and Pontrandolfo, 2017)

The analysis of 28 existing EIPs according to the developed framework shows that some of the listed features characterize all the clusters, while others that less frequently occur can be used to differentiate among EIPs. It results that a high heterogeneity among firms, the presence of collaborative networks inside the EIPs and with external stakeholders, and the governmental support bring about the adoption of a wider range of sustainable practices.

The survey performed by (Veleva *et al.*, 2015) among organizations belonging to the Devens' (USA) EIP interestingly showed as the main motivations to join the EIP were related to competitiveness critical issues such as gaining access to shared infrastructure, having the opportunity of knowledge sharing, joint sourcing, building local supply chain, and reducing the weather related and business related risks, more than building up physical exchanges of materials. Regarding sustainability practices, they were considered as source of competitive advantage, and in particular energy efficiency, materials efficiency, good infrastructure, and employee skills and well-being.

## 2.3 NATIONAL PROGRAMS

Many national or global programs support (or supported) IS related programs and EIPs development.

Japan developed its Eco-Town Program, expanding the focus of previous industrial environmental management initiatives, to foster IS initiatives with the dual objective of stimulating new industry development and addressing waste management concerns, in particular the shortage of landfill sites. The program established 26 Eco-Towns around Japan: 14 Eco-Towns primarily contributed to improving industry's productivity, whilst 10 Eco-Towns primarily contributed to reducing environmental impacts; the public investment subsidies triggered private investment: about 1.5 recycling plants were built without government subsidy for every recycling plant built with government subsidy (Van Berkel, Fujita, Hashimoto and Geng, 2009). A three stages EIP program was established in 2005 in Korea, to improve the competitiveness of the local aged industry. After the first stage, the 47 industrial symbiosis projects at five pilot sites produced a significant GHG reduction, achieving 51% of the target set by Korea's low-carbon green growth policy, together with considerable economic benefits (189 million US dollars) due to cost savings and revenue generation (Park, Park and Park, 2016).

China began to support the EIP strategy in the early 2000s with the enactment of both cleaner production and circular economy promotion laws; a national Chinese EIP standard was firstly designed in 2006, successively revised in 2009, 2012 and 2015 (Huang *et al.*, 2019a), while there is no internationally accepted standard for EIPs. The standard provides five classes of indicators to be fulfilled related to: economic development, industrial symbiosis, resource conservation (such as the "application ratio of renewable energy", to be ≥ 9%), environmental protection, and information disclosure. The UNIDO promotes EIP pilot projects mainly in developing and emerging economies, and developed 18 industrial parks in 7 countries (China, Colombia, India, Morocco, Peru, South Africa, Viet Nam); this experience leads to the designing of an international EIP Framework and other standardized documents (handbook and toolbox) to mainstream EIPs in developing countries.

In Europe, EIPs belong typically to planned networks IS typology (Domenech *et al.*, 2019) and are mainly located in UK, Germany, The Netherlands and Italy.

In Italy, the *ecologically equipped industrial areas* (Area Produttiva Ecologicamente Attrezzata – APEA in Italian language) were introduced by a national law in 1998 (D.Lgs.112/1998) and implemented by some regions that can decide the features and the goals of their APEAs based on the peculiar characteristics of the territory and the production system. The APEAs represent a model of eco-compatible local industrial development that can play a role in the evolution of the local industrial systems, and especially the local industrial districts, towards the EIP model (Taddeo, 2016). APEAs are characterised by high environmental quality standards, aiming at minimising the impact of processes and activities and improving the well-being of communities. They must be provided with shared spaces and physical and immaterial infrastructure management systems and a management body, that can be a mixed public-private organism. The management body is an almost unique characteristic of the APEA model, while the main EIPs characteristics (shared services and technologies, landscape ecology, utility sharing, networking, and involvement of local stakeholders) are fulfilled by all the APEA samples analysed by (Daddi, Tessitore and Testa, 2015), excluding the by-product exchanges.

## 2.4 SUSTAINABILITY ASPECTS

As the previous discussion disclosed, the EIP model allows the integration of the three dimensions of sustainability, promoting synergies among the economic development, the natural environment and local communities.

The EIP model addresses 7 out of the 17 Sustainable Development Goals (SDGs) established by UN, and can support the countries effort in achieving the targets set by the SDGs. Figure 5 briefly outlines the EIP model contributions to the SDGs.


*Figure 5. EIP model contributions to Sustainable Development Goals set by UN[7].*

The sustainability principles, guiding the development of industrial symbiosis as well as EIPs projects, provide the key criteria for assessing environmental, social and economic aspects of decisions to be taken. The best EIP configuration has to be chosen comparing different scenarios built up by minimizing the negative impacts and maximizing the positive ones.

Thus, quantitative sustainability indicators are needed to assess the sustainability level of an EIP and support decisions on its design. A wide research effort has been devoted to the identification of suitable sustainability indicators analyzing the existing EIPs, the EIPs national or regional Programs' regulations, and performing surveys among industry managers, practitioners, policy makers and other relevant stakeholders. A comprehensive review of the sustainability indicators used for assessing eco-industrial parks behavior can be found in (Valenzuela-Venegas, Salgado and Díaz-Alvarado, 2016). The authors compiled a wide repository of indicators, discussing and classifying them by sustainability dimensions; each indicator can belong to one or more sustainability dimension (the energy-related indicators are discussed in the chapter 2 of this thesis).

EIPs can be considered as innovation platforms facilitating actions concerning environmental impacts, not only with the end-of-pipe approach but also at a systemic level, such as adopting a life-cycle perspective (Winans, Kendall and Deng, 2017). According to this view, EIPs' sustainability is frequently evaluated using life-cycle assessment (LCA) based analyses (Kim, Ohnishi, *et al.*, 2018; Martin and Harris, 2018).

[7] https://sdgs.un.org/goals

# 3 LOW CARBON INDUSTRY TRANSITION THROUGH RES INTEGRATION

Global $CO_2$ emissions from the industry sector include energy-related emissions (both indirect - for energy bought from external suppliers - and direct, when originating from fuel combustion) and $CO_2$ emissions from industrial processes (direct emissions). According to IEA (International Energy Agency) statistics and IRENA (International Renewable Energy Agency) calculations, about 75% of the energy used in industry is process heat (of which about half high temperature heat, T> 400°C), and the rest is for mechanical work and electricity (lightning, computers, etc.) (IEA/OECD and Cédric Philibert, 2017).

Therefore, low-carbon strategies in industry should be based both on the sustainable transformation of production processes, including energy efficient technologies, and the use of sustainable energy sources (UNIDO, 2017).

A summary of the energy-related $CO_2$ emissions reduction strategies applicable at industry level is provided in the next Table 3.

| Strategy | Area of application | Advantages | Limitations |
|---|---|---|---|
| Enhancing energy efficiency and energy conservation | Applied both to processes, auxiliary services and industrial buildings | Energy saving from 10% to 20% easily achievable. | May involve extensive capital investment. |
| Increasing usage of clean fuels | Substitution of coal by natural gas for power generation | Natural gas emits 40–50% less $CO_2$ than coal due to its lower carbon content and higher combustion efficiency; cleaner exhaust gas (lower particulates and sulfur dioxide emissions). | Higher fuel cost for conventional natural gas. |
| Adopting multi-generation systems | Buildings, single firm, industrial cluster | Increasing conversion efficiency and energy system flexibility | System higher complexity |
| Use of renewable energy | Buildings, single firm, industrial cluster | Use of local natural resources; no or low greenhouse and toxic gas emissions | Applicability may depend on local resources availability and cost; intermittency. |
| Afforestation and reforestation | Single firm, industrial cluster | Simple approach to create natural and sustainable $CO_2$ sinks | Restricts/prevents land use for other applications |
| Carbon capture and storage | Applicable to large $CO_2$ point emission sources | It can reduce vast amount of $CO_2$ with capture efficiency >80% | Not at commercial scale |

*Table 3. Summary of energy-related $CO_2$ emissions reduction strategies (adapted from (Leung, Caramanna and Maroto-Valer, 2014))*

Once the efficiency and electricity saving objectives have been achieved, the electrification of industrial processes supported by the use of combined renewable energy sources (RES), offers a recognized potential for emissions reduction where resources abundance allows to lower the cost of electricity, also fostered by the recent and rapid cost reductions in some renewable electricity-generating technologies that have led to the emergence of new, affordable options (IEA/OECD and Cédric Philibert, 2017).

Considering renewable power, industries have two ways to adopt it: they can both install RES plants to produce the power locally, or improve the share of power produced by renewables (e.g. hydropower) in the mix of the bought electricity; the two solutions can also be combined. Also regarding procurement various purchasing modes are available: onsite owned renewable plants, onsite contracted plants, renewable energy certificates or green tariffs.

Recent technological advancements now provide solutions for adopting intermittent RES through methods such as distributed energy generation and smart grids. 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 (Ozorhon, Batmaz and Caglayan, 2018). 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 (Weeber *et al.*, 2017). But a favorable regional environment, with existing capacities in renewables can stimulate firms in adopting renewable energy (Horbach and Rammer, 2018).

### 3.1 RES FOR INDUSTRIAL APPLICATIONS

The potential for renewable energy use in industry has been widely explored, to support the sustainable development and foster the low carbon shift of manufacturing sector. Techno-economic and environmental assessment demonstrate the benefits of possible integration options (Taibi, Gielen and Bazilian, 2012).

The main renewable energy sources suitable for industrial application are biomass, solar radiation (thermal or photovoltaics), ground heat, and wind. This section presents a brief overview of the potential for the utilization of RES in industrial applications.

A number of RES introduction projects have been realized by industries worldwide, as summarized by (IEA/OECD and Cédric Philibert, 2017) that analyzed the different integration schemes (Table 4) and project drivers and motivations for industries, that may vary widely, depending on location and energy needs (Table 5).

| *Industry* | *Integration scheme* | *RES technology* | *Plant capacity* |
|---|---|---|---|
| *Volkswagen Chattanooga manufacturing plant (USA)* | Green power procurement agreement (20 years) with a third-party producer | Solar photovoltaic | 9. 5 MW |
| *Vestyfen brewery (DK)* | Onsite installation of fully owned and operated renewable power generation unit | Wood boiler (replacing an oil-fired boiler) | 4 MWth |
| *Diavik Diamond Mines – off-grid mine (Canada)* | Onsite installation of fully owned and operated renewable power generation unit | Onshore wind farm | 9.2 MW |
| *Tenon Manufacturing (New Zealand)* | Onsite installation of RE production assets and process adaptation | Geothermal steam fueled kilns (replacing gas-fuelled) | 27 MWth |
| *Jain Irrigation System Ltd (India)* | Paradigm shift involving renewable raw materials and energy, and valorisation of by-products | Tomato transformation by-products to biogas + biocompost | |

*Table 4. Some industrial projects involving RES integration.*

| *Industry* | *Drivers/motivations* | *RES technology* | *Results* |
|---|---|---|---|
| Codelco- Gabriela Mistral Division mine (Chile) | Hedging from fuel and grid price volatility and the risk of future increases, and in some cases reduced energy costs | Thermal solar project | Annual savings of EUR 5.3 million |
| Australian Tartaric Products (Australia) | Improved energy supply reliability | CHP plant fueled by grape waste | |
| Tenon Manufacturing plant (New Zealand) | Increased productivity | 27-MWth geothermal plant | Productivity increased by 5% |
| Epperidge Farm plant (United States) | Additional revenue opportunities through sales of excess energy to the power grid or heat networks, or to other industries | Solar PV plant | |
| Hima Cement Ltd's (Uganda) | Greater coherence with corporate environmental and local commitments | Coffee husk project (waste recovery) | |

*Table 5. Some drivers guiding RES installation in industry.*

The various integration schemes demonstrate that a wide range of possibilities can allow the integration of RES at industrial level, depending on the company's motivations and objectives. The drivers of RES projects can be related to the reduction of energy cost and environmental impacts, the revenue opportunities provided by a surplus of energy, and the enhancing of energy supply reliability.

However, regulatory, economic and technological barriers hinder the deployment of RES in industry sector, along with lack of awareness and insufficient investments in innovation. A single SME find it difficult to deal with these barriers: it must face a complex decision problem that involves technical, legal and economic feasibility. The proper renewable energy technology or technologies have to be chosen, as well as the size of the plant based on the SMEs' energy demand and profile, and the possible overproduction handled (Pechmann and Zarte, 2017).

### 3.1.1 Bioenergy and Biomass

Bioenergy accounts for about 80% of the energy generated by renewable energy carriers worldwide. The main reason is that it can directly substitute fossil fuels and, unlike the other RES, can be stored. $CO_2$ emissions savings can be obtained even with ORC (Organic Rankine Cycle) plants that show low electric efficiency (about 15%): more than 400 kg per MWh converted (Strzalka, Schneider and Eicker, 2017). Traditionally, bioenergy is the most used renewable energy within industry, and in particular by energy intensive industry as well as in EIPs context, for example employing residual biomass for producing renewable thermal energy in biomass-fired CHP. Biomass feedstock include residues from agriculture or forestry, wood, energy crops, oil-rich algae, biological residues and the organic component of municipal and industrial wastes. Some industries produce large amounts of biomass as waste or by-product (e.g. bagasse from sugar cane processing plants) (Liew *et al.*, 2017a). The biomass conversion processes for energy production can be divided in:

- Thermochemical: combustion, pyrolysis and gasification
- Physical-chemical: for the production of biodiesel
- Bio-chemical: for the production of biogas or ethanol

Biomass can also be converted into chemicals for making plastics and other materials typically produced from petroleum.
A biomass technologies classification, based on the resulting energy, aggregates the technologies into three main groups (Tafarte et al., 2020):

- Biomethane (or vegetable oil) powered cogeneration plants
- Biogas plants with local combined heat and power generation (including wood gas CHPU)
- Thermodynamic cycle biomass power plants (wood-fire power plants)

Bioenergy technologies for power generation, with the exception of biomethane CHPU, include two sub-processes: the raw material is first converted in a secondary energy carrier, namely biogas or steam, and then the energy carrier is converted into heat and power. As regard biomethane-CHPU, it works as a single conversion process, where the fuel is converted into electricity and heat.

Bioenergy has the benefit of long storability in feedstock form, a costless form respect to the energy storage systems needed to compensate for the variability in power production from wind and solar. From the environmental point of view, bio-liquids (bioethanol, biodiesel), bio-gases (biomethane), and bio-solids (biocharcoal) are considered near term available substitute for fossil fuels, because of their carbon neutrality; however, competition for land use, protection of biodiversity, life-cycle emissions and air quality are still open issues in the biomass field (Bataille *et al.*, 2018).

### 3.1.2 Solar

Solar energy is the most abundant source of energy on earth. In recent years, the global installed capacity of solar energy generating systems has rapidly grown thanks to improvements in technology and performance, cost competitiveness and enhanced environmental awareness. Sunlight can be converted into thermal and electrical energy. A variety of available technologies can be used in industrial facilities to fulfill the facility demand, sized to supply the required energy or integrated with conventional systems (Mekhilef, Saidur and Safari, 2011).
Solar panels can be installed on the roof spaces available on industrial buildings, service buildings and warehouses, or on car shelter in parking areas and landfill areas.
The conversion technologies for solar energy are thermal collectors and photovoltaic (PV) modules. In addition, solar thermal and PV technologies can be combined together to form a single module called a Photovoltaic/Thermal system (PV/T).

#### *3.1.2.1 Solar thermal*

Solar thermal technologies allow the conversion of solar irradiation into heat. Solar collectors are heat exchangers that absorb the radiation and convert it into useful heat transferred to a fluid. They can be concentrating (parabolic through, Fresnel lens, etc.) collectors, that have to be mounted on a sun-tracking system, or non-concentrating (flat-plate, evacuated tube) collectors working in stationary conditions; sun-tracking systems cover larger areas.

Most industry sectors use energy for heating, depending on the type of process and products to be processed, with a 50% of thermal energy demand in the range of 30°C to 400°C (Ramaiah and K.S. Shashi Shekar, 2018). So, from the point of view of industrial use, the technical significant parameter of a solar thermal system is the typical operating temperature: flat plate collectors and evacuated tube collector can be used in low temperature applications (up to 120°C) that cover 30% of the industrial processes segment, while parabolic trough collectors and Fresnel collectors are suitable for processes requiring temperature higher than 250°C, covering 22% of industrial needs. Central receiver systems or "solar towers", which can achieve higher temperatures still, have so far developed in the power sector only (IEA/OECD and Cédric Philibert, 2017). The Table 6 shows some of the characteristics of the solar thermal collectors used in the industrial field, including the working temperature range and the possible industrial application (Settino *et al.*, 2018).

| Collector type | Absorber type | Motion | Heat transfer medium | Typical temperature range (°C) | Possible industrial applications |
|---|---|---|---|---|---|
| Flat Plate Collector | Flat – non concentrating | stationary | Water or air | 30–80 | Crop drying, washing and cleaning, pasteurization, pre-heating of boiled feed water |
| Evacuated Tube Collector | Flat – non concentrating | stationary | Water or air | 50–200 | Space heating, cooling, sterilization/evaporation |
| Compound Parabolic Concentrator | Tubular – line focusing concentrator | Regular adjustment | Water or air | 60–240 | Space heating, cooling, sterilization/evaporation |
| Parabolic Trough Collector | Tubular – line focusing concentrator | One axis | Water, air, thermal oil | 60–400 | sterilization/evaporation, spray drying |
| Linear Fresnel Reflector | Tubular – line focusing concentrator | One axis | Water, air, thermal oil | 60–250 | sterilization/evaporation, spray drying |
| Parabolic Dish Collector | Point focusing concentrator | Two axes | Water, air, thermal oil | 100–500 | sterilization/evaporation, spray drying |
| Heliostat field collector | Point focusing concentrator | Two axes | Air, steam, molten salt | 150-2000 | Electricity, superheated steam, thermochemical reactions |

*Table 6. Solar thermal collectors for industrial applications (adapted from (Mekhilef, Saidur and Safari, 2011; Ramaiah and K. S. Shashi Shekar, 2018; Settino et al., 2018))*

The integration of solar industrial process heating is generally implemented for pre-heating steps, direct steam generation and process heating. The most common applications include, for example, the production of hot water and steam, drying and dehydration processes, pre-heating, curing, pasteurization, sterilization and industrial space heating/cooling. The relations among solar thermal technologies, their operating temperature range and applications are visually represented in the Figure 6. A most detailed overview of industrial processes where solar heating is in use, with respect to industry sector and collector technologies can be found in (Farjana *et al.*, 2018).

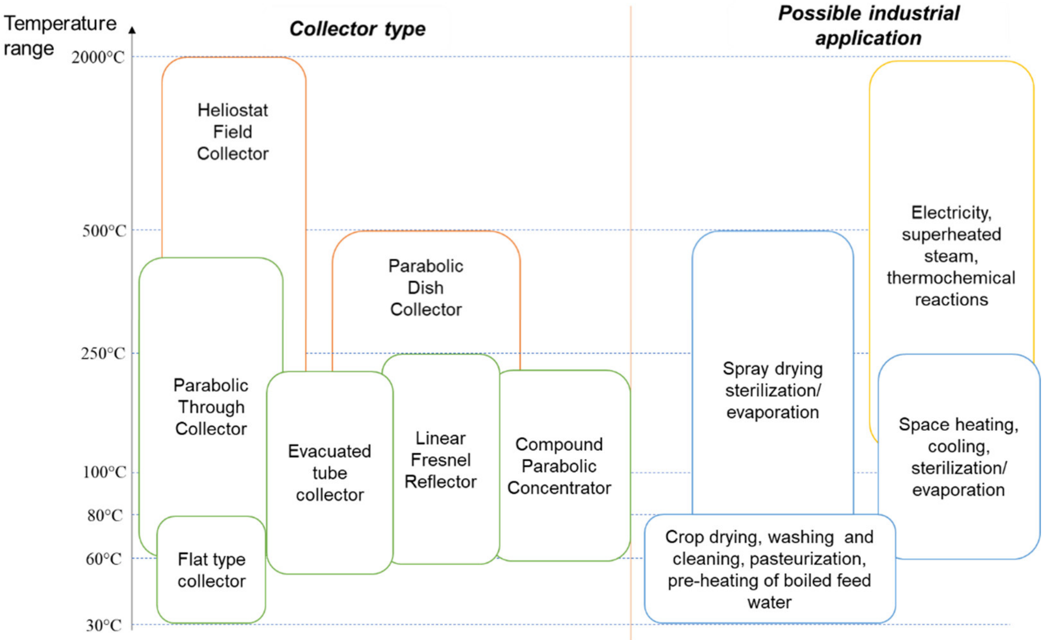


*Figure 6. Diagram displaying the possible industrial applications of different solar collector technologies depending on operating temperatures.*

At low temperatures, the cost of solar heat, produced by non-concentrating thermal technologies, is competitive with heat cost from fossil fuels. So, the industry needing low-temperature heat such as the food and beverage industry, the service industry, and the textile industry, are the main fields of application of solar heat.

#### *3.1.2.2 Solar photovoltaics*

Photovoltaic (PV) systems, made up of PV cells as basic units, convert solar radiation directly into electricity, thanks to the electro-optics properties of semiconductor materials (such as silicon), and namely to the photoelectric effect. Photovoltaics is a fast-growing market, with more than 385 GW cumulative global installed capacity in 2017[8].

PV devices at different level of technology readiness made up with a variety of materials are currently available, but the most efficient commercially available PV cells, for terrestrial applications, are made of silicon (Benati *et al.*, 1996; Stefancich *et al.*, 2001; Butturi *et al.*, 2002); other commercially available PV cells are thin-film cells, made of few micrometers thick layers of semiconductor materials such as cadmium telluride (CdTe). According to the Fraunhofer Institute for Solar Energy Systems (ISE)[9], silicon-based PV modules account for the 93% of global PV installed capacity in 2017 (60.8% multi-crystalline silicon and 32.2% mono-crystalline silicon), while the share of thin-film PV modules is 4.5% (CdTe 2.3%, a-Si 0.3% and CIGS 1.9%).

Other types of PV cells are mainly used for niche applications (e.g. multi-junction solar cells are mainly developed for spatial applications and concentrators) or at early development stage (e.g. organic, perovskite cells).

The most diffuse commercial PV systems consists of flat modules, made up of silicon-based PV cells as basic units, connected in series or parallel, the mounting structures that point panels towards the sun (stationary or sun-tracking) and the inverter that converts the generated direct current into alternating current. Thanks to the modular structure, PV systems can be sized to meet the requested power need; moreover, a PV plant can be grid connected or stand-alone, and integrated with storage units.

The conversion efficiency of commercial flat PV modules made up of traditional PV cells (mono- and multi-crystalline silicon cells) has grown up to more than 22% (e.g. mono-crystalline SunPower modules[10]) and 20% (e.g. multi-crystalline Canadian Solar modules[11]), meaning that an approximate area of respectively 4.4 $m^2$ and 5.3 $m^2$ is required to generate 1kW peak power (excluding BOS efficiency). Thin film modules with a conversion efficiency of 8.5% require an area of approximately 11.7 $m^2$ to generate 1 kW peak power.

The electrical energy generation (in kWh) depends on the available irradiation, the system efficiency (including technology parameters such as temperature coefficient) and the spectral response of the PV cells material.

Concentrating photovoltaic (CPV) systems are also available (Antonini *et al.*, 2015; Antonini, Butturi and Zurru, 2015). Optic devices (lens or mirrors) concentrate the sunlight on the receiver where the PV cells are assembled, and the whole system is mounted on a sun-tracker. The CPV systems are classified based on the concentration ratio, that defines the equivalent sun radiation reaching the receiver, as low-medium concentration systems (5 to 200 X, i.e. from 5 to 200 times the sun irradiance hitting the earth surface at the sea level) and high concentration systems (up to 500 X).

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[8] IRENA (2018), Renewable capacity statistics 2018, International Renewable Energy Agency (IRENA), Abu Dhabi

[9] ©Fraunhofer ISE: Photovoltaics Report, updated: 27 August 2018

[10] https://us.sunpower.com/products/solar-panels

[11] https://static.csisolar.com/wp-content/uploads/2019/12/28165744/HiKu_CS3W-P_High-Efficiency_en.pdf

#### *3.1.2.2.1 BIPV*

A specific sector of PV energy converters is BIPVs (building integrated photovoltaics) sector. BIPVs are PV modules specifically developed to be integrated in the building envelope (roof, façade or windows if transparent) by replacing building materials such as tiles, both for retrofitting solutions and new projects aiming at obtaining green certifications or fulfill NZEB (Nearly Zero Energy Building) requirements (Biyik *et al.*, 2017). Flexible thin-film modules are commercially available for installation on industrial buildings and warehouse roofs.

#### *3.1.2.2.2 Hybrid PV/T*

The PV/T is a hybrid technology consisting of solar photovoltaic cells (PV) and solar thermal components integrated into a single module. The PV/T module generates both electricity and heat that can reach an overall efficiency of 70% (Ramos *et al.*, 2017). The PV/T modules can be used in the domestic and in the industrial field, for the purpose of preheating air or water, the contact fluids that can be used to cool the PV cells maximizing their electrical performance.

### 3.1.3 Wind

Wind is directly related to solar energy since it flows when the sun's rays unevenly heat the air in the atmosphere.

A wind energy system harvests and converts wind energy (the rotating kinetic energy) into electrical energy. Any wind power system typically consists of tower, wind turbines (rotor and blades), generators, power transformers, and a connection to the power grid, if grid-connected. Wind turbines can be installed individually or grouped as wind farms. Utility-scale plants can be off-shore or land based. Onshore turbines have 50–100 m tower heights with a rotor diameter of 50–100 m. Wind turbines work on a rotor and hub assembly speed of 12–20 RPM, being capable of generating power at low wind speeds (3-4 m/s). Small wind turbines are available for water pumping or domestic applications (Kumar *et al.*, 2016). Wind turbines suitable for applications in urban built environment are under development (Stathopoulos *et al.*, 2018).

More than generated from on-site installations in industrial areas, usually wind power is bought to add a significant renewable energy share to the energy mix used by industry (Finn and Fitzpatrick, 2014).

### 3.1.4 Geothermal

Geothermal energy is a form of heat embedded in Earth, that can manifest as geo-thermal fluid (e.g. hot water or vapour) that can be used to generate electricity. In this form, its availability is geographically limited to some regions. The direct use of geothermal energy is the common form of exploitation of this renewable energy, with a significant prevalence of shallow ground heat applications for heating, ventilation and air conditioning. Ground-source heat pumps have the largest energy use and installed capacity worldwide, accounting for 70.95% of the installed capacity and 55.30% of the annual energy use (Lund, Bertani and Boyd, 2015); the distribution of thermal energy used by category is summarized in the Figure 7.

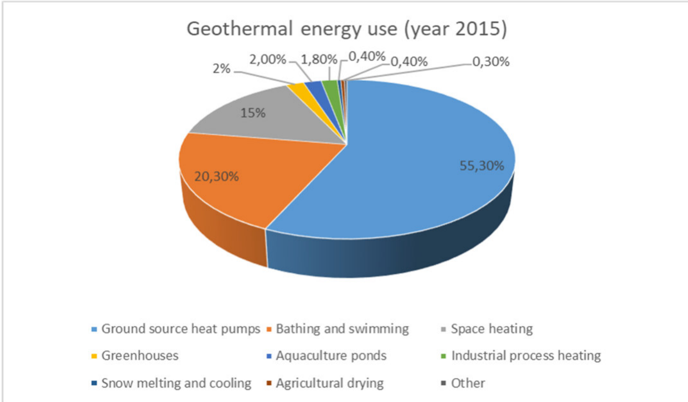


*Figure 7. Distribution of thermal energy use by category (year 2015). From* (Lund, Bertani and Boyd, 2015).

Shallow geothermal systems (commonly closed loop/open loop geo-exchange systems) exchange thermal energy with the first 100-200 m of the ground and are designed to avoid thermal depletion of the soil. Exchangers are typically connected to heat pumps for winter heating and summer cooling of buildings and underground thermal energy storage (UTES).

Despite the widespread diffusion in residential and commercial sectors, as stated before, these systems are still little used in the industrial sector, mainly due to higher temperature requirements of most industrial processes but also to scarce knowledge of the technology potentiality. Effective industrial applications are thermal energy storage when combined with solar thermal energy collectors or for collecting waste heat, and service buildings (shed, office) heating and cooling. Innovative applications to industrial processes are currently explored, see for example (Focaccia *et al.*, 2016).

#### *3.1.4.1 Heat pumps*

According to the energy policy of the EU (Directive 2009/28/EC), heat pumps (HPs) are considered as contributing to EU renewable energy share goals, provided that the energy they supply exceeds the primary energy they consume. The heat pumps are energy efficient systems able to transfer heat from a low temperature heat source to a higher temperature heat sink. The seasonal performance factor, accounting for the energy output/input ratio, is the parameter that determines if a heat pump can be considered as a renewable energy source according to the 2013/ 114/EU Commission Decision.

The heat sources can be air, water or the ground, so the heat comes from geothermal and solar energy. The performance of the different type of heat pumps is essentially location and application specific: air source HPs are less efficient in low temperature regions, so their application is widely diffused in warmer climates, while ground source HPs are more diffused in colder regions. Water source HPs are the most efficient, but the need for a neighbor waterbody (or a storage tank) poses cost and environmental concerns.

Since HPs are high-electricity demand systems, and particularly ground source HPs, they can be combined with PV and battery energy storage systems, furtherly reducing GHG emissions (Litjens, Worrell and van Sark, 2018). Solar assisted heat pumps have higher performance coefficient and are often viable solutions for places with mild climates and high solar radiation.

A great research effort is ongoing to improve the performance of heat pumps, both from the scientific and the industrial side (Gaur, Fitiwi and Curtis, 2021).
The analysis of a dual-source HP, using the innovative integrated multi-source energy harvesting approach (both air and ground are external heat sources), demonstrated the environmental validity of the technology in comparison with both air and ground source HPs. The variation in the energy mix used to power the heat pump during the use phase is the most influencing factor in the final

environmental assessment (Marinelli *et al.*, 2020). The combination of the two sources allows for a wide range of geographical applications.
A network of decentralized heat pumps is being installed to serve an innovative low-temperature district heating project[12] in Germany, exploiting water-filled mines as geothermal boreholes. The DH system includes two levels mine, making available two water temperatures suitable for heating and cooling, and a cascade two-pipe network allowing the re-use of "waste" heat (or cold) water coming from a consumer to the next one.

### 3.2 Carbon Capture and Storage (CCS)

CCS is not a renewable energy technology, but it is often associated to renewables as it is considered a key strategy to meet $CO_2$ emission reduction targets, mainly considering the energy intensive industries (EIIs), and it is sometimes related to industrial symbiosis. Since CCS approach is gaining more and more interest from scholars, institutions and policy makers, this section provides a brief overview of the potentiality of such a technology.
The principle underpinning the CCS technology is that the $CO_2$ formed during the processes involving combustion can be captured to avoid its dispersion in the atmosphere, and successively stored in geological formations (or under the Ocean).
The main process steps of CCS technology are $CO_2$ capture, separation, transport, and storage; leakage, monitoring, and life cycle analysis are also considered as relevant aspects.
The suitable $CO_2$ capture process is determined by the type of combustion process; $CO_2$ capture technologies are the main costs of the whole process. The second step requires the separation of $CO_2$ from the flue/fuel gas stream prior to the transportation step. After separation, $CO_2$ can be transported to the storage site. The system of transport, ranging from road tankers to ships and pipelines, is a key feature of any CCS project, that must be reliable, safe and economically feasible. The final destination of extracted $CO_2$ can be geological reservoir such as deep saline aquifers, oil and gas reservoirs or deep coal beds (where the $CO_2$ can be injected to recover methane), or deep Ocean.
A comprehensive review of CCS technologies is provided in (Leung, Caramanna and Maroto-Valer, 2014)
Some scholars (Neves *et al.*, 2020b) suggested that captured $CO_2$ can also be transported to nearby facilities for its industrial utilization, transforming it into fuel and other products, such as chemicals and materials, in an industrial symbiosis approach.

During the 13th SET-Plan[13] Conference (held in November 2019), some European EIIs' managers (the President of the European Cement Association and the PM of Equinor) presented new technologies and projects aiming at supporting the transition to climate-neutral industry. Beside the development of cleaner processes, some CCS projects were presented, and the CCS was recognized as a very promising technology to reduce energy intensive industries emissions, since the electrification of EIIs would require a huge amount of electricity increasing significantly the indirect emissions. Present barriers, more than technological, are related to the lack of regulations and of a market to support the technology development.

### 3.3 RES Cost Evaluation

Many cost indicators are used in academic studies to analyse the cost/benefit ratio of an energy system including RES and hybrid RES (i.e. systems combining different type of renewable technologies); the main to be optimized are the Net Present Value (NPV) of the system and the levelised cost of electricity (LCOE).

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12 https://www.construction21.org/articles/h/d2grids-interview-5th-generation-district-heating-and-cooling-system-a-link-between-the-city-s-coal-past-and-modern-energy.html?from-notification=20210114

13 The Strategic Energy Technology Plan (SET Plan) was launched by European Union in 2007, with the aim of transforming energy production and use in the EU to achieve EU worldwide leadership and accelerate the European energy system's transformation towards a competitive low-carbon economy with consumers at the centre.

The method of LCOE allows a comparison of power plants with different generating and cost structures. The LCOE results from the comparison of all costs, which arise throughout the lifetime of the power plant for the construction and operating of the plant, with the sum of the generated amount of energy throughout the life cycle. The calculation can be conducted either on the basis of the NPV method or the so-called annuity method (Kost *et al.*, 2018). The first method best represents the reality. These and other cost indicators are listed in the Table 7.

| **Cost indicator** | **Math formulation** | **Description** |
|---|---|---|
| LCOE (in €/kWh)<br>(on the basis of NPV) | $LCOE = \frac{I_0 + \sum_{t=1}^{n} \frac{A_t}{(1+i)^t}}{\sum_{t=1}^{n} \frac{M_{t,el}}{(1+i)^t}}$ | $I_0$ Investment expenditure<br>$A_t$ Annual total cost (fixed and variable operating costs + residual value/disposal costs) per year t<br>$M_{t,el}$ Produced amount of electricity in kWh per year<br>i Real interest rate in %<br>n Economic lifetime in years<br>t Year of lifetime (1, 2, ... n) |
| LCOE (in €/kWh)<br>(on the basis of annuity method – version 1) | $LCOE = \frac{(I_0 + \sum_{t=0}^{n} \frac{A_t}{(1+r)^t}) \times ANF}{\frac{\sum_{t=1}^{n} M_t}{n}}$ | $ANF_{t,i} = \frac{i \times (1+i)^t}{(1+i)^t - 1}$<br>is the annuity factor |
| LCOE (in €/kWh)<br>(on the basis of annuity method – version 2) | $LCOE = \frac{(I_0 \times ANF) + A}{M}$ | Here, the LCOE is calculated with the assumption that the amount of electricity produced annually (M) and the annual operating costs (A) are constant over the entire period of observation |
| Annualized cost of system (ACS) | $ACS = TSC \times \frac{i(1+i)^L}{(1+i)^L - 1}$ | TSC is the total system cost including maintenance and installation of all the components, i is the discount rate and L is the total lifetime of the system |
| NPV (net present value) | $NPV = \sum_{k}^{T} \frac{(C_{in} - OC_{RES}) - CC_{RES}}{(1+j)^k}$ | NPV is used in capital budgeting to analyze the profitability of an investment ($CC_{RES}$) for a certain time (T years) at a specific discount rate j. The NPV is the difference between the present value of cash inflows and the present value of cash outflows ($C_i$ – $OC_{RES}$). |
| LCCA (life-cycle cost analysis) | $LCCA = \sum_{k}^{T} \frac{(CC_{RES} - OC_{flows})}{(1+j)^k}$ | The LCCA value takes into account all cash outflows related to future activities (operation costs, taxes for self-consumption, and electrical and thermal energy costs) but without cash inflows. All costs are discounted and total to a NPV |
| NPC (net present cost) | $NPC = \sum^{NP} C_{sale\_k} + \sum^{NP} C_{end\_k} - C_{invest} - \sum^{NP} C_{replace\_k} - \sum^{NP} C_{M\&O\_k}$ | $NPC_{sale\_k}$ is the income obtained by selling off the components to be replaced (for a grid-connected system it also includes the income from energy sold to the grid), $NPC_{end\_k}$ is the income obtained by selling system components at the end of the lifetime of the system, $C_{invest}$ is the total investment cost, $NPC_{replace\_k}$ is the cost of replacement of components during the lifetime of the plant and $NPC_{M\&O\_k}$ is the cost of maintenance and operation of all the components |
| COE (cost of energy) per economic unit | $COE = \left[\left(\frac{i(1+i)^L}{(1+i)^L - 1}\right) \times \left(\frac{P}{8760}\right)\right] + (M\&O)$ | P is total installed capacity and M&O is maintenance and operation costs of the system |

*Table 7. Cost indicators used for optimisation of renewable energy systems (Pechmann and Zarte, 2017; Kost et al., 2018; Singh and Bansal, 2018).*

Some reference cost parameters of renewable technologies mainly used in industry, as reported by (Pechmann and Zarte, 2017), are shown in Table 8.

| RE technology | Capacity range | Capital cost | Operating cost (€) |
|---|---|---|---|
| Photovoltaics | 40-2000 kW | 1040 €/kW+7300€ | 2% of the CC |
| Wind | 30 kW (42m) | 5630 €/kW | 1600 € |
| | 900 kW (76m) | 1450 €/kW | 10000 € |
| CHP | ~ 300 kW | 837 €/kW | 2.98 €/h |
| | ~ 1500 kW | 434 €/kW | |
| Solar heat | 5-1000 $m^2$ | 801 €/$m^2$ + 64€ | 2% of the CC |

*Table 8. Some reference costs for renewable technologies as in (Pechmann and Zarte, 2017).*

The LCOE of the main renewable technologies calculated by the Fraunhofer Institute for Solar Energy System (ISE) in 2018 (Kost *et al.*, 2018) are summarized in the next Table 9. The solar and wind technologies values are calculated considering different German locations, with different mean insolation and wind availability. Biogas plants are intended as power plants which burn biogas (solid, liquid or gaseous bio-fuels) only for electricity generation. As a reference, conventional Combined Cycle Gas Turbine (CCGT) power plants are considered and brown coal plants. While for PV technology the global horizontal irradiance (GHI) for north, central and south Germany is considered, as far as concern wind, bioenergy, and conventional power plants, the range of full load hours (FLH) is used to calculate LCOE.

| RE technology | Capacity range | GHI / FLH | LCOE (€$cent_{2018}$/kWh) (range min-max referred to GHI and FLH ranges) |
|---|---|---|---|
| PV rooftop small | 5-15 $kW_p$ | 950-1300 kWh/$m^2$·y | 7.23 ÷ 11.54 |
| PV rooftop large | 100-1000 $kW_p$ | 950-1300 kWh/$m^2$·y | 5 ÷ 8.43 |
| PV utility-scale | > 2 $MW_p$ | 950-1300 kWh/$m^2$·y | 3.71 ÷ 6.77 |
| Wind onshore | 2-4 MW | 1800-3200 h | 3.99 ÷ 8.23 |
| Wind offshore | 3-6 MW | 3200-4500 h | 7.49 ÷ 13.79 |
| Biogas | > 500 $kW_{el}$ | 5000-7000 h | 10.14 ÷ 1474 |
| CCGT | 400-600 MW | 3000-4000 h | 7.78 ÷ 9.96 |
| Brown coal | 800-1000 MW | 6450-7450 h | 4.59 ÷ 7.98 |

*Table 9. LCOE calculated for different renewable technologies. Specific investments are taken into account with a minimum and maximum value for each technology. All the cost and additional assumption refer to the German market (see* (Kost *et al.*, 2018)*); kWp refers to "peak kW".*

*Chapter 2*

# Industrial Energy Symbiosis

Within the industrial symbiosis approach, the IES includes a multi-dimensional mix of sustainable and innovative technical solutions as well as organizational strategies to implement inter-firm energy exchanges, joint projects for energy efficiency and for collective power generation and aims at reducing the energy-related carbon footprint of industry and supporting circular economy approaches.

In a recent literature review on energy-based industrial symbiosis focused on case studies, (Fraccascia *et al.*, 2020) categorized energy-based IS exchanges into three groups: energy cascade; fuel replacement; and bioenergy production. All the three exchange categories can be implemented both within a single company or among different companies. Moreover, in energy cascade, energy flows can be directly implemented between production processes or sent to an energy recovery facility and then redistributed to other processes; regarding fuel replacement, the waste can be directly used to replace fuel or converted in an alternative fuel, e.g., pallet, through a waste treatment process; lastly, bioenergy production has a geographic dimension: the waste exploited for bioenergy production can be produced in rural, industrial, or urban areas. The authors also distinguished four categories of drivers, barriers and enablers: financial, technical, regulatory and institutional (here intended as issues related to the organizational structure of involved firms, their business models, and their strategic behavior in implementing IS). Although the cited authors consider the application of the IES approach to EIPs a limitation to the possible exchanges, this study considers the EIP technical and organizational structure as an enabler of energy exchanges (both from the technical, financial, regulatory and institutional point of view) since, more than material flows, energy flows are highly influenced and limited by the distances.

Thus, this chapter focuses on energy- based industrial symbiosis within EIPs, considering also the integration of RES. It also presents the modelling methods mainly used in the academic research. Lastly, a sustainability criteria system suitable for analyzing energy synergies, including RES within EIPs is developed.

This chapter is partially based on the papers:

-*Renewable energy in eco-industrial parks and urban-industrial symbiosis: A literature review and a conceptual synthesis,* published in 2019 in the Journal Applied Energy, vol. 255, 113825, doi: 10.1016/j.apenergy.2019.113825.

- *Distributed renewable energy generation: a critical review based on the three pillars of sustainability*, published in 2018 in the PROCEEDINGS OF THE 23rd SUMMER SCHOOL FRANCESCO TURCO, vol. 1, pp. 179-185, AIDI - Italian Association of Industrial Operations Professors.

# 1 ENERGY SYMBIOSIS WITHIN EIPS

According to (Timmerman, Vandevelde and Van Eetvelde, 2014), a low carbon energy system should include energy efficient technologies, maximize the integration of local RES and enable energy exchanges between firms. Since most of the decarbonization solutions are characterized by high initial investment costs with a long pay-back period (Habert *et al.*, 2010), a viable pathway to reduce the carbon footprint of the industry sector, while saving costs, is represented by the industrial energy symbiosis (IES). Within the framework of the industrial symbiosis, the IES considers the energy synergies that can be created between firms: the sharing of energy-related resources and energy exchanges networks. It is an effective model to promote energy conservation measures, reduces the dependence from fossil fuels and enables renewable energy sources uptake at the industrial level.

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 (Horbach and Rammer, 2018). EIPs spatial configuration and the existing infrastructures facilitate the creation of energy exchange networks, to share the available surplus energy, and the installation of co-financed power units. Energy exchanges can include flows of electrical, thermal, chemical or other types of excess energies.

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) (Fabrizio *et al.*, 2017). The starting point to develop a $CO_2$ emissions reduction plan, is to classify the ways the energy is used in industry (Table 10, (Aro, 2009)):

| **Form of energy use** | **Description** | **Type of industry** |
|---|---|---|
| Building energy users | The production requires small amounts of electricity and heat; HVAC and lighting are the main loads. | Non-energy intensive industries (assembly lines, the production of equipment and machines) |
| Major users of electricity for process/production | Electricity use in process/production is clearly bigger than the building electricity consumption. | Pulp and paper, metal production, production of plastic products and glass making. |
| Major users of heat for process/production | Heat use in the process/production is clearly bigger than the building heat consumption. Heat means energy forms which are transmitted by pipes such as water, steam and hot oils. | Pulp and paper, dairies, part of the textile industry, chemical industry, production of rubber products. |
| Direct combustion users | In some applications, the product can be heated directly or indirectly by fire and/or flue gases. Especially natural gas is good in many applications. | Cement and lime production, glass and brick production, bakeries and production of metals. |

*Table 10. Ways the energy is used in industry (adapted from (Aro, 2009))*

The analysis of the thermal and electrical needs of companies and the comprehensive evaluation of energy inputs-outputs for all industrial processes enable an energy baseline to be calculated and define where inter-plant or inter-company connections can be established.

Since the work of (Fichtner, Frank and Rentz, 2004), different inter-firm energy supply concepts have been investigated as promising approaches for achieving cleaner energy production. The specificity of energy flows poses some issues:

- energy exchanges can require dedicated infrastructure with related investments, that can be considerable mainly in the case of heat exchanges and must take into account the long-term aspects (such as future demand, supply and regulations variations);
- to minimize energy losses along the transportation networks, the exchanging firms should be in close proximity;
- electricity and heat storing, when production and demand are not simultaneous, require costly infrastructure.

EIPs structure allow to overcome some of the previous issues: in fact, they 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. In addition to inter-firm energy exchanges, joint projects for energy efficiency and for collective energy production can be implemented. Energy clustering could bring some advantages to single firms, mainly due to a reduction in infrastructure investments cost due to the economies of scale and in operating costs. Higher energy security and reliability can also be reached thanks to a reduced dependence from the energy market.

Energy symbiosis within EIPs creates exchange networks that can be classified, according to (Afshari *et al.*, 2016), 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 (e.g. incinerators fed by wastes to supply energy); and in the third type, waste or unused energy (from processes) are shared among companies. This last type of network, that allows to create more energy symbioses, 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 (Kastner, Lau and Kraft, 2015). 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 (Togawa *et al.*, 2014). 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 (heat exchangers, heat pipes, condensing boilers and heat pumps), to produce thermal energy for heating or cooling, or converting technologies (Organic Rankine Cycle, Kalina cycle and trilateral cycle) to convert the waste heat into electric and mechanical power (Huang *et al.*, 2017).

The recovery of industrial waste heat is suggested by (Marchi, Zanoni and Zavanella, 2017) 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.

An overview of energy management solutions to reduce the industry related carbon footprint within EIPs was presented by (Maes *et al.*, 2011), with the aim of designing an improved carbon neutrality strategy for industrial parks located in the Flanders Region in Belgium. The main advantages for firms of energy clustering are linked to the reduction of investment and operational costs, but it can be considered also the reduced dependence on energy market prices and higher operational reliability (energy security), the increased affordability of clean energy technologies that lowering the company's carbon footprint could improve its image and the working conditions.

Although the sharing of sustainability goals is considered among the main drivers for initiating or participating to an EIP project, the firms' main objectives are economic competitiveness and costs lowering. Some indirect benefits, such as increased flexibility or innovation can also be considered. A survey performed among the companies located within the Devens' (USA) EIP showed that the main sustainability challenges identified by study participants included reducing cost of energy (and thus improving energy efficiency) mentioned by 61% of interviewed organisations. The park offers services to help businesses save energy: professional audit to support firms in identifying efficiency opportunities with a payback period of two years or less, energy consumption benchmarking services and employee engagement guidelines (Veleva *et al.*, 2015).

A set of indicators for assessing the sustainability of eco-industrial parks in terms of energy has been reviewed by (Valenzuela-Venegas, Salgado and Díaz-Alvarado, 2016); many of them consider the environmental point of view, however, only one, among the sustainability indicators, considers the renewable resources and none the share of renewable energy within a park. Only few authors (Wang *et al.*, 2017) suggest an index considering the renewable energy use ratio, i.e., the proportion of energy produced by renewable sources used by companies. According to this view, the Chinese EIP standard system, set in 2015, introduces a new sustainability indicator "Usage rate of renewable resources" (Huang *et al.*, 2019b), as well as the Vietnamese programme that uses the share of energy produced by renewables as a key indicator for the EIP sustainability evaluation (Massard, Leuenberger and Dong, 2018).

The energy symbiosis in EIPs is further investigated below considering the use of RES and the modelling approaches.

# 2 ENERGY SYMBIOSIS INVOLVING RES WITHIN EIPS

This section presents an overview of the academic studies analysing the energy strategies adopted in EIPs, with a focus on the use of RES.

Starting from a list of relevant terms based on the focal topics: “Eco-industrial parks”, “carbon emissions reduction”, “industrial energy symbiosis”, and “renewable energy sources”, a broad range of keywords and similar concepts emerged Table 11.

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

*Table 11. Overview of the concepts associated with the literature research.*

Three main constructs emerged from the literature review: energy symbiosis involving RES in EIPs, energy symbiosis modelling and energy organizational strategies within EIPs. The three constructs are discussed in the following.

Beside the heat exchanges, the most used renewable energy source used within EIPs is biomass.

Organic waste materials, such as sludge and waste wood, are considered the most sustainable biomass supply for fuel or energy production, and are a frequently used within industrial parks for recovering waste that cannot be otherwise reused or recycled, thus avoiding landfill (Patricio *et al.*, 2018; Zhang, Du and Wang, 2018). 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 neighboring 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, Pakarinen and Melanen, 2011) 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 other case studies demonstrate that energy exchange relationships among companies involving the use of residual heat from waste incineration or anaerobic digestion and heat recovery from byproducts within an EIP lead to a collective GHG emissions reduction (Ban, Jeong and Jeong, 2016; Park, Park and Park, 2016).

The type of fuel used in shared power plants and heat supply systems significantly affects the level of carbon emissions within the parks. 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. Through a process-based LCA method, that assesses direct and indirect energy-related GHG emissions, applied to a number of Chinese industrial parks (Guo *et al.*, 2016) show 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. However, despite the major academic efforts to demonstrate the feasibility and effectiveness of the use of renewable energy sources within EIPs, progress is still slow. For instance, considering the large scale Chinese national demonstration program to facilitate the eco-transformation of industrial parks, only 3 EIPs out of 106 share RES power plants and in total the renewable-fuelled power plants (biomass, bioenergy, solar, wind, hydro and geothermal) account for about 1% of the total power generation capacity (Guo *et al.*, 2018).

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. 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. 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 (Beier, 2017).

An effective method of increasing the RES utilization efficiency at the industrial park level is to combine heat and power generation using 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. These systems also allow for the recovery of heat generated by electricity production, resulting in an overall efficiency approaching 90% (Martinez *et al.*, 2017). 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 (Korhonen, 2001). 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 (Weeber *et al.*, 2017).

## 2.1 Distributed Energy Resources and Multi-Energy Systems

Distributed energy resources (DER) approach is widely considered to be the main pathway towards an effective integration of discontinuous sources (such as RES) into the energy system (IRENA, 2019). Distributed energy systems (DES) can be sized to meet specific demand needs and installed on site, aiming at utilizing local fuels; the DER configuration, typically, includes distributed generation (small to medium scale modular energy generation units, typically ranging from few kW to tens of MW) 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 (Lund *et al.*, 2017). A distributed energy system guarantees reliability, scalability and cost-effectiveness, and is environmentally friendly (Verbong and Geels, 2010), promoting the diversification of energy sources and the use of low-carbon technologies (Alanne and Saari, 2006). On the other hand, small scale renewable energy systems have long been considered as environmentally and social sustainable solutions (Rae and Bradley, 2012) and are now economically affordable.

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 micro-grids. Industrial smart micro-grids, consisting of inter-connected loads and DES including RES, can be developed and operated in a controlled and coordinated way, optimizing the control of the individual units and the grid itself. In smart-grids, the use of ICT and smart technologies allow to manage the local grid and the integration of DER (Anaya and Pollitt, 2017). Bidirectional energy trading is enabled and demand side management (DSM) can enhance customers service, allowing the reduction of peak-to-average ratio of the power system and the energy costs for consumers (Liu and Hsu, 2018). Available advanced sensing and digitization allow to match supply and demand, facilitating energy savings. The new bi-directional energy system brings about the concept of “prosumer”, the energy user (household, community or industry) that is also an energy producer (Green and Newman, 2017). The number of stakeholders involved in the distributed renewable energy approach is then bigger than it was in the centralized system.

In the industrial context, reference is usually made to the use of various renewable energy sources for generating both electricity and heat (hybrid-RES or HRES), in combination with other generation systems such as tri-generation technologies (combined cooling, heat and electricity), energy storage systems and energy distribution networks. In literature, this configuration is described as multi-energy systems (MES) (Mancarella, 2014), distributed energy supply (Yang *et al.*, 2016), distributed multi-energy systems (Mavromatidis *et al.*, 2019) or distributed multi-generation (Chicco and Mancarella, 2009), with slightly different connotations.

The concept of smart multi-energy system (SMES or smart-MES) (sometimes called Smart Multi-Energy Grids) extends the concept of the smart-grid (Martinez et al., 2017), typically defined within the limitations of the electricity sector, by integrating multi-energy carriers. The smart-MES architecture promotes a coordinated energy strategy within EIPs, and it is the most explored and widely recognized effective option for the integration of RES in the electrical system of an EIP; it can be modelled to support decision-makers in identifying and choosing the better generation options including RES.

The smart 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. Within industrial parks the loads have different owners, as may the generation and storage units, so decentralized control can be the preferred solution.

A suitable tool for the integrated management of a smart MES can be modelled as an energy hub (EH). (Mohammadi *et al.*, 2018) 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 (Figure 8).

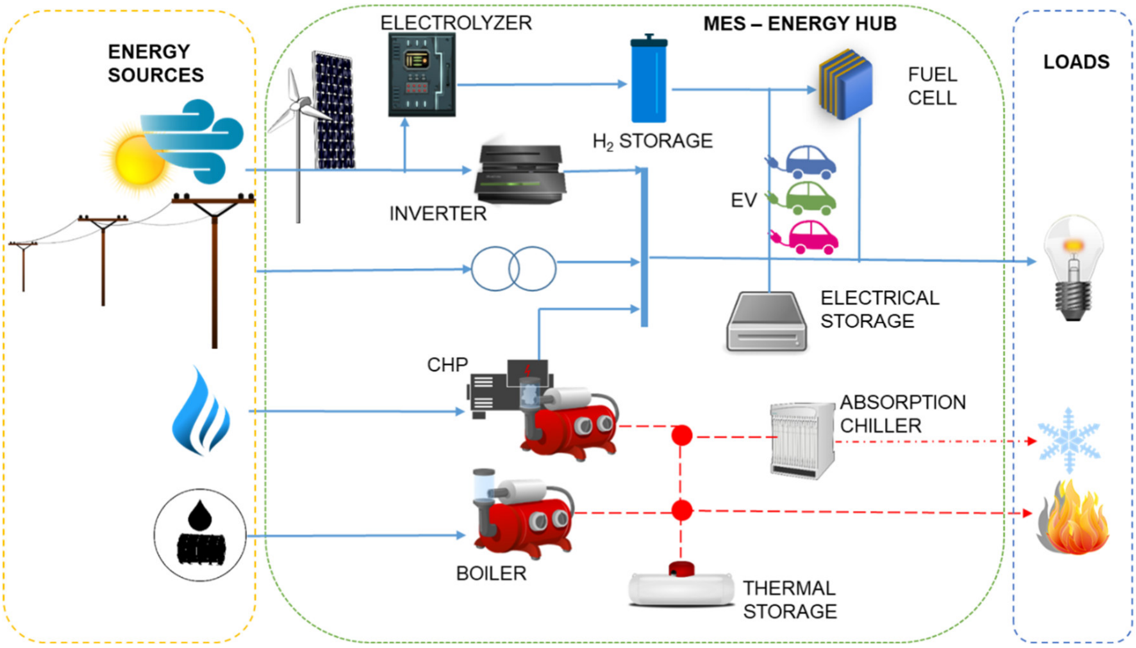


*Figure 8. A schematic diagram of the energy hub concept.*

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 (Ma *et al.*, 2018).

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 (Mancarella, 2014).

## 2.2 Energy organizational strategies within EIPs

The strategies for reducing greenhouse gas emissions at an industrial park level can be energy efficiency measures, both at the industrial operational level and the buildings level, and energy conversion systems using available renewable sources. At industrial operational level more efficient processes and machineries as well as auxiliary services, the introduction of heat exchangers and fuel switching to renewables are the main options; at the buildings level solutions as effective insulation, relighting or the application of NZEB (nearly-zero energy buildings) approach can be considered.

These 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 (Côté and Liu, 2016).

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 (Horbach and Rammer, 2018). 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 (Maes *et al.*, 2011).

In the EIP energy system scheme individual companies can be either connected to energy conversion units or to an internal energy network any energy overproduction by means of storage options, supplying a number of companies; the local network can be connected to both the regional distribution grid and the district heating (DH) network (Timmerman, Vandevelde and Van Eetvelde, 2014).

(Feng *et al.*, 2018) 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 plantation carbon sink), and, once the park energy consumption and emissions are known, the energy strategy can be designed to maximize the carbon offset. The technical measures aimed at maximising the carbon offset are illustrated in Figure 9.

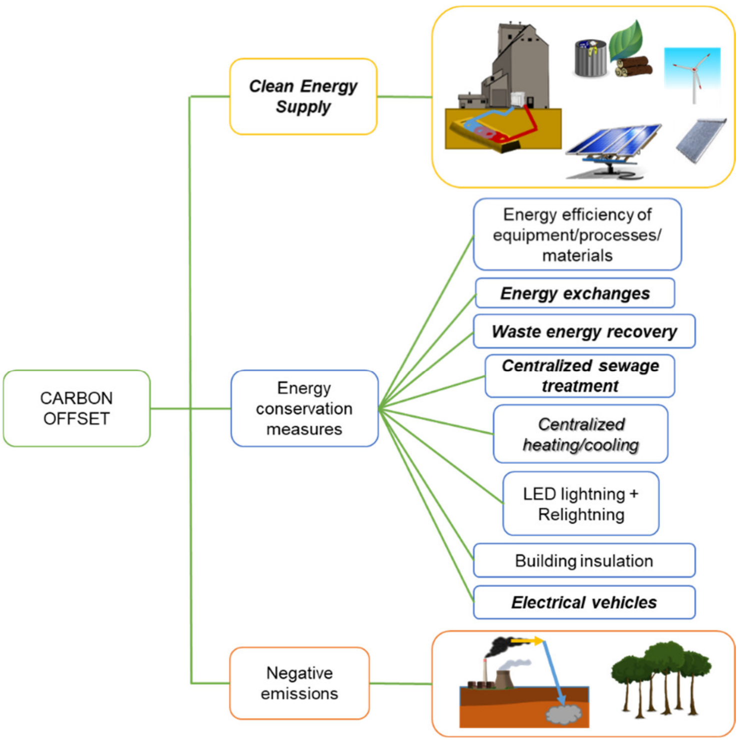


*Figure 9. Carbon offset maximization technical measures.*

The energy-based possible strategies at EIP level, as collected from literature, are summarized in the Figure 10. 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.

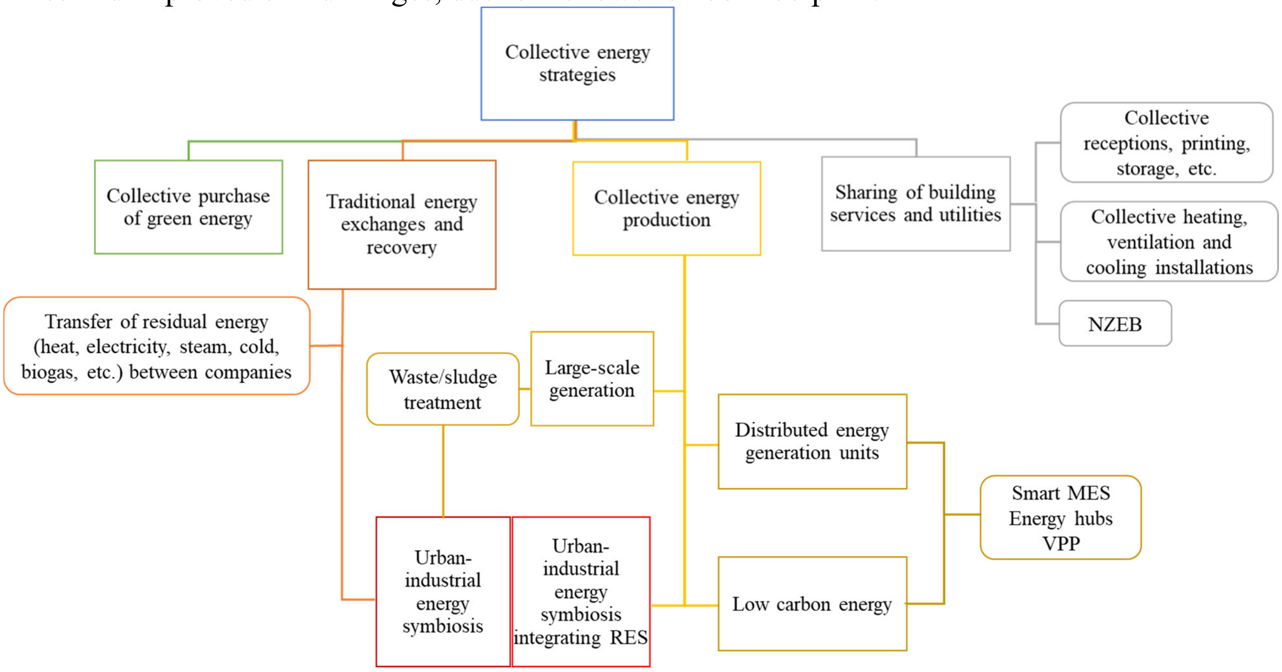


*Figure 10. Conceptual framework outlining the inter-firm cooperation schemes that can foster the adoption of emission-mitigating technologies.*

As the cooperation among businesses enables knowledge gaps to be overcome and reduces the investment, maintenance, and management costs of the energy infrastructure to be shared, the collective effort to increase the use of RES is a viable method for reducing the carbon footprint of industry.

The introduction of renewable energy cooperatives, a form of clustering involving firms and other local stakeholders, can 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. For instance, the specific characteristics of a cooperative required for facilitating the energy transition of the Port of Rotterdam, one of Europe's major industrial clusters, is analysed by (Hentschel, Ketter and Collins, 2018). Organizational issues, clear targets and milestones, trust and close communication among partners are the main attributes required for a successful project.

In this way, 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 (Karner, Theissing and Kienberger, 2016), thus minimizing the environmental impact of electricity production at local level (Dong et al., 2014).

Within the EU, a comprehensive regulation framework to support the energy clustering has been recently provided by the Renewable Energy Directive (RED II)[14] on the Promotion of the Use of Energy from Renewable Sources, that EU27 countries must transpose into national law by June 2021. The RED II establishes that consumers are entitled to become renewables self-consumers (also called "prosumers", being simultaneously energy producers and consumers), and having the right to

[14] Official Journal of the European Union L 328/82. Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the Promotion of the Use of Energy from Renewable Sources (Recast). 2018.

consume, store or sell renewable energy generated by their own plants. The “prosumers” can be both individuals (households and non-energy SMEs) and collective in electricity projects managed by a third party (art. 21 of RED II), or part of Renewable Energy Communities organised as independent legal entities (art. 22 of RED II). This regulation can act as an “enabling framework” for the collective energy projects, since the energy communities and energy clusters can be considered as mirror images, governance and technological, of the same concept (Lowitzsch, Hoicka and van Tulder, 2020).

The RED II has been transposed into Italian law by the end of 2020 with the law decree 162/19 (art. 42bis); resolution 318/2020/R/eel of the Italian Regulatory Authority for Energy, Networks and Environment (ARERA) and the DM 16/09/2020 of the Ministry of Economic Development, providing a new business model to take advantage of renewable technologies installation. This kind of business model can promote the industrial energy-based joint projects and also the energy exchanges between industrial and urban areas.

The urban-industrial symbiosis (UIS) approach is the subject of the chapter 4 of this thesis.

# 3 MODELLING ENERGY SYMBIOSIS - STATE-OF-THE-ART

One of the goals of the energy symbiosis modelling, and the main goal that the research presented in this thesis aims to achieve, is to create willingness for the potential participants to adopt the symbiosis methods. In this perspective, the basic condition for the energy symbiosis approach to be viable is to demonstrate that the sum of benefits achieved by working collectively is higher than working as a stand-alone facility, where the advantages resulting from the symbiosis approach are typically discussed in terms of economic, environmental and social benefits, often referred to as the 'Triple bottom line'. This will be the focus of the model development presented in the chapter 3 of this thesis.

Two main research trends can provide theoretical frameworks and quantitative tools to support the modelling of energy symbiosis network: the EIPs design modelling, the renewable energy planning, including the DER, HRES, and MES modelling.

## 3.1 ECO-INDUSTRIAL PARKS MODELLING

The EIP main goal is to realize a sustainable industrial system minimizing the energy and raw materials use through materials and energy exchanges, while preserving companies' economic competitiveness. The interconnected industrial system that can be realised within an EIP increases the complexity of the engineered systems, requiring both engineering optimisation and the economic trade-off (Kuznetsova, Zio and Farel, 2016). From a modelling point of view, the top-down design of EIPs can be treated as a multi-objective problem, involving numerous stakeholders with potentially conflicting objectives and a mix of technical, environmental and social issues.

Due to the peculiarity of the resources, most optimization methods used in the design of EIPs separately consider the types of symbiotic relationships involving materials, energy, and water (Boix et al., 2015). So, the studies presenting EIPs modelling methods can provide energy symbiosis modelling tools if energy exchanges (mainly heat) are investigated. In particular, the multi-objective optimization approach, a methodology widely used in the industry, allows to design EIPs improving industrial sustainability dimensions (objective function), deciding over the presence of inter-firm connections or the flow rates between firms, and the acceptable emissions (decision variables); all the decisions are subject to constraints, that can be context considerations, process and operations requirements and limitations. The main optimised objectives are related to economic and environmental sustainability dimensions, while the social dimension is almost never considered, probably due to the difficulty of defining quantitative indicators, or sometimes considered as part of the other two dimensions (Valenzuela-Venegas, Vera-Hofmann and Díaz-Alvarado, 2020).

The economic objective is also the main reason for the firms to be involved in IS projects. In single-objective optimization the cost to be minimized is often the net present value (the annualized global cost), sometimes a periodic evaluation of costs or a project-based evaluation considering also operational costs on a temporal range. Linked to the cost of the network, is the evaluation of the network complexity represented by the number of links: each flow can be associated to a binary variable equal to zero if the connection does not exist, and equal to one if a link is created.

The most used environmental objective is the natural resource consumption, that can be water or energy, to be minimised. The energy utilities to minimize can be electricity, heat or fuel gases. The total energy consumption is often accounted as a part of the total economic cost.

Beside resources conservation, a great interest is devoted to the evaluation of the environmental impacts of inter-firm symbiosis. Among others, LCA methods are used to study the impact of all exchange types within EIPs; LCI studies have been performed to analyse the impact of industrial symbiosis on GHG, the economic input-output LCA and life cycle cost analysis (LCCA) have been applied to analyse all economic costs of interlinks between businesses.

Commonly used methods for the bottom-up approach to EIPs are game theory, often associated to emergy based analysis, to explore acceptable network structures with respect to the economics of the participating companies or to produce incentives or penalties to induce park tenants to more environmentally sound practices. Fuzzy logic methods have been applied to EIP settings; agent-based modelling has also been proposed as a means to study and predict viable ways of evolving EIPs (Yazdanpanah and Yazan, 2018; Yazan, Yazdanpanah and Fraccascia, 2020).

## 3.2 Renewable energy planning – DER, HRES and MES Modelling

Multi-objective optimization is widely used in energy planning and energy resource allocation, due to the conflicting objectives and uncertainty characteristics of such projects.

Renewable energy planning as well uses this methods, analyzing economic constraints, technology limitations, environmental and social benefits (Pohekar and Ramachandran, 2004). The most used formulations consider both linear and non-linear optimization techniques, depending upon the RES type, the objective function and the area of application. A comprehensive review of the optimization method for renewable energy in the various application areas are provided in (Iqbal *et al.*, 2014).

Considering the smart grid configuration, the multi-objectives optimization techniques planning, designing and operation of DER are reviewed by (Naz *et al.*, 2017); the authors analyse the application area of the considered optimization techniques (Table 12) and present some mathematical formulations for commonly used objectives relating to resource management in microgrids.

| **Optimization type** | **Description** | **Reviewed applications** |
|---|---|---|
| MILP (Mixed integer linear programming) | It can deal with the problems having linear objective function and linear constraints but have no nonlinear constraint. | -Minimizing the total cost of:<br>-transferring the electricity from/to the main-grid,<br>-operation of distributed generator,<br>-starting up and shutting down the distributed generator<br>-Minimizing uncertainties due to intermittent sources<br>-Minimizing GHG emissions |
| MINLP (Mixed integer non-linear programming) | It refers to problems in which objective/constraints have continuous and discrete variables as well as have nonlinear functions | -Minimizing the cost of electricity and pollution of combined heat and power system<br>-Minimizing the cost of electricity bills and maximizing the user comfort level in smart home<br>-Minimizing the uncertainties due to RES voltage deviation and electrical energy losses<br>-Economical and technical best allocation of distributed generators by considering its uncertainties |
| LP (Linear programming) | It is a technique to get best solution (such as maximum profit and low cost) in mathematical form which is represented by linear relationship. | -Minimizing:<br>- the bill of energy<br>- total load shedding amount while considering power as a constraint<br>-operational cost<br>-environmental impact<br>-Maximizing:<br>-the stability of the system<br>-the reliability of a system including storage<br>-the utility function |
| NLP (Non-linear programming) | Nonlinear relationships | -Optimal operating strategy<br>-Minimizing cost and GHG emissions, while considering cost, power, capacity and security as constraints |

*Table 12. Taxonomy of optimization techniques applied to DER in microgrid configuration as presented in (Naz et al., 2017).*

The most used technique for the design, operation, and optimization of MES is mixed integer linear programming (MILP), due to the combination of accurate system description and acceptable computation complexity. Deterministic MILP, often associated to sensitivity analysis, robust optimization and stochastic programming are the most used approaches to deal with uncertainty of the input data. However, the uncertainty of the input data is more relevant in terms of the system operation than of the system design (Gabrielli *et al.*, 2019).

The great majority of HRES modelling and optimization studies are based on the economic and reliability constraints, addressing techno-economic objectives (Singh and Bansal, 2018). However, the sustainability goals require to consider also environmental impacts over the entire components and project life-cycle and the social dimension as well. A more holistic approach to HRES is proposed by (Eriksson and Gray, 2018), who developed a model including a four-dimensional objective function with weightings applied to monetary cost, technical performance, environmental footprint and socio-political factors (Figure 11) to optimize a multi-component energy system in which hydrogen is one of the energy vectors.

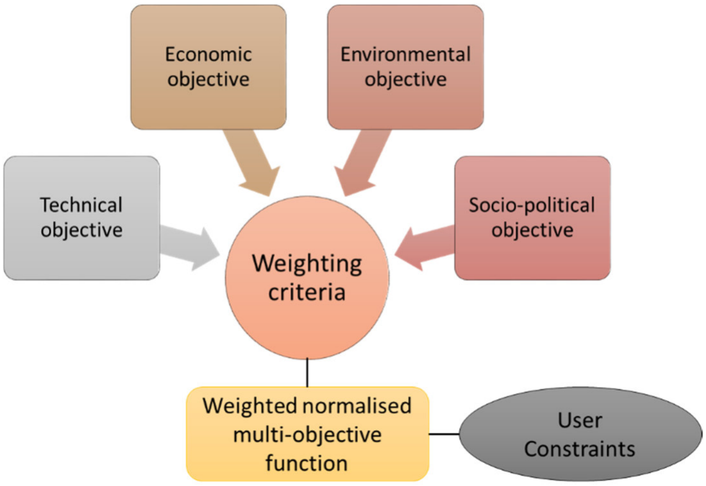


*Figure 11. Four-dimensional model for HRES including hydrogen optimization* (Eriksson and Gray, 2018).

The optimization is then performed by means of a four-dimensional multi-objective meta-heuristic algorithm starting from the Particle Swarm Optimisation algorithm.

### 3.3 Energy Symbiosis Modelling

Energy symbiosis modelling can be viewed as an aspect of EIP design. After evaluating the potential viability of creating inter-plant connections or joint energy projects, the advantages of such networks must be investigated and demonstrated.

(Fichtner, Frank and Rentz, 2004) proposed a classical procedure to assess the technical and economic aspects of implementing inter-firm energy supply projects and the subsequent environmental effects. It involves:

1. the analysis of the state-of-the-art;
2. the analysis of strategies without co-operation (business as usual case);
3. the identification of technical solutions for the inter-firm energy supply;
4. the economic evaluation of the identified technical solutions;
5. the ecological evaluation of inter-firm energy supply concepts.

(Timmerman, Vandevelde and Van Eetvelde, 2014) 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. According to the aforementioned study, 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.

(Kastner, Lau and Kraft, 2015) reviewed modelling methods to identify and establish viable inter-company exchanges: they found that pinch analysis, total site analysis and mixed integer linear programming (MILP) are the main methods used to optimize energy exchange networks. The authors built up the framework to optimize an EIP by considering energy management presented in the next Figure 12.

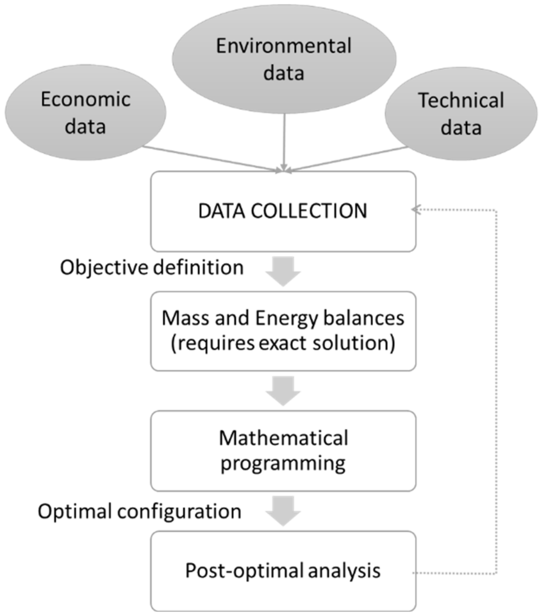


*Figure 12. Approach to optimize an EIP.*

When considering energy exchanges, the main issues are related to the variety of data to be collected and the need for binary variables representing the existence or not of an energy flow, thus requiring a MILP formulation. Existing energy symbiosis models mainly focus on heat exchanges and aim to simultaneously minimize costs and emissions related to energy exchanges, and to maximise the number of energy exchanges (Afshari *et al.*, 2016).

A multi-stakeholder MILP model for heat exchanges have been developed by (Afshari, Farel and Peng, 2018), considering the economic objective at firm level, the environmental level and both the economic and the environmental objectives at EIP level. The social criterion is the most difficult to mathematically formulate because it involves non quantifiable concepts. A proposal for integrating the social dimension in energy symbiosis modelling is provided by (Afshari *et al.*, 2020). An objective function is introduced in the model to maximise the index valuing the "social value preference", representing the values of suppliers perceived by customers. The social value index is quantified and evaluated through the application of the Analytic Network Process (a multicriteria decision-making technique).

# 4 SUSTAINABILITY IN ENERGY PROJECTS

Energy supply is essential for human life and well-being, so sustainability is a key aspect of every energy project. UN Sustainable Development Goal #7 calls for ensuring “access to affordable, reliable, sustainable and modern energy for all”. The pathway to achieve the SDG7 goals requires guaranteeing secure energy supply to all, improving energy conversion efficiency, increasing the share of renewable energy sources and implementing new business models.

Energy related sustainability issues have been widely analyzed in scientific literature (Turkson *et al.*, 2020) both in relation to energy planning and management, considering the energy supply technologies and infrastructure and including renewable technologies that are essential for energy sustainability, and to the distributed energy architecture.

The studies differ in the type and number of sustainability indicators considered, methodologies for the assessment (e.g., life cycle assessment) and methods for integrating sustainability aspects (e.g. subjective approach, multi-criteria decision analysis, etc.) (Santoyo-Castelazo and Azapagic, 2014).

This section presents a critical analysis of the main energy-related sustainability indicators collected, to build up an up-to-date set of sustainability related criteria, suitable for future research applications and for supporting decision making processes.

In literature, two are the main evaluation methods accounting for the three sustainability dimensions and providing comprehensive sets of indicators in the renewable energy field: lifecycle-based methodologies and multi-criteria decision analysis (MCDA) methods. Lifecycle based methods provide large databases covering environmental, social and human health impact quantification. The multi-criteria decision approach allows the integrated sustainability evaluation, accounting for complex and evolving biophysical and socio-economic systems.

The need to handle simultaneously technical, economic, social and environmental issues led to the use of multi-criteria analyses tools to formulate and solve the configuration problem addressing multiple objectives and including the most of criteria that better fits the sustainability goals to be reached. These techniques have become increasingly popular in designing renewables integration in the energy market substituting simpler approaches (such as cost–benefit or cost-effectiveness approach and energy ecological footprint) because of the multi-dimensionality of the sustainability goals (Løken, 2007), so a vast set of sustainability-related criteria is available in this research field.

## 4.1 Energy supply systems

With the aim of supporting the decision-making in energy supply systems planning and management oriented towards sustainable development, a typical, though dated, set of evaluation criteria of the energy supply systems has been compiled by (Wang *et al.*, 2009). The main criteria collected are presented in the Table 13; the last column shows the percentage of papers, on those reviewed, that use each single criterion.

| Dimension | Criteria | Comments | % of use |
|---|---|---|---|
| Technical | Efficiency | The main criterion of energy sustainability | 60 |
| | Exergy efficiency | It computes the efficiency of a process taking the second law of thermodynamics into account | 12 |
| | Primary energy ratio | Or primary energy savings, due to the use of RES | 16 |
| | Safety | Both technical and social | 36 |
| | Reliability | It depends on the quality of the equipment, its maintenance, the type of fuel. | 36 |
| | Maturity | (consolidated technologies are close to reaching the theoretical limits of efficiency) | 12 |
| Economic | Investment cost | | 86 |
| | O&M cost | | 46.5 |
| | Fuel cost | | 32 |
| | Electric cost | It is the cost for the consumers | 25 |
| | NPV | | 18 |
| | Payback period | Sometimes also energy payback time | 14 |
| | Service life | | 14 |
| | Equivalent annual cost (EAC) | The cost per year of owning and operating an asset over its entire lifespan | 14 |
| Environmental | $CO_2$ emissions | $CO_2$ is mainly released from energy systems through the combustion of coal/lignite, oil, and natural gas. | 91 |
| | $NO_x$ emissions | $NO_x$ is produced during the combustion of fossil fuels and biomass, especially combustion at high temperatures. | 52 |
| | CO emissions | | 13 |
| | $SO_2$ emissions | Gaseous emission of coal/lignite, oil and combined cycle natural gas power plants. | 35 |
| | Particle emissions | Particles are mainly released by coal/lignite and oil as well as biomass and photovoltaic power plants (during their cell construction). | 22 |
| | Non-methane volatile organic compounds | | 13 |
| | Land use | | 43.5 |
| | Noise | | 26 |
| Social | Social acceptability | It is a qualitative criterion | 21 |
| | Job creation | | 47 |
| | Social benefits | It expresses the local social progress (qualitative) | 26 |

*Table 13. The typical evaluation criteria of energy supply systems (adapted from (Wang et al., 2009)).*

The table 13 shows a broad set of criteria, where some of the criteria can be included in others. Job creation can be included in social benefits, while the gas and particle emissions contribute to local pollution, so they have a direct impact on the health and an indirect impact on the social state of the community too. Some environmental recapitulative criteria are often used: effects on natural environment, climate change and acidification (that includes $NO_x$ and $SO_2$ emissions contributing to acid rain). Social acceptance (or public acceptability) of energy projects and technologies can include aspects such as local or regional issues also included in environmental aspects (e.g. land-use change issues, landscape and visual impact, noise), distrust or uncertainty towards unknown technologies, and perception of health and safety risks (the emphasis here is on public perception of health and safety issues, as opposed to calculated health and safety risks) (Santoyo-Castelazo and Azapagic, 2014).

The technical and economic criteria are the mostly used, together with the environmental ones, and often the social domain is neglected or underestimated, mainly due to the complexity of managing qualitative criteria.

Some authors convert the *GHG emissions reduction* in an economic criterion, considering the avoided environmental compliance costs or taxes. Among the economic criteria, the *LCOE* can be used instead of the electricity cost and the EAC, while the *investment opportunities*, triggered by the installation of new and clean technologies, is sometimes considered. The *waste reduction* as well as the *adoption of environmental management systems* can be included as environmental criteria. Lastly, social indicators account for the social aspects of the energy project; they are related to that of social impact assessment, a methodology to monitor and analyze the consequences of the implementation of new technologies in social context. Other social indicators to be considered are: *societal equity*, linked to satisfying the essential requirements of individuals in terms of easy accessibility to energy, affordability and no disparities, *human health and safety* (that can be considered as external costs due to hospital and medication, loss of productivity etc.), *energy security, diversity and safety*, to help to provide affordable priced and consistent energies to all, *cultural heritage protection*, *risk analysis and management,* and *intergenerational issues*, considering the mitigation of climate change (for instance through the global warming potential – GWP index) and depletion of fossil fuel reserves (Maxim, 2014; Santoyo-Castelazo and Azapagic, 2014; Luthra, Mangla and Kharb, 2015).

Not all the available criteria must be used, but the proper ones should be chosen depending on the goals of the sustainability evaluation, the technology to be evaluated, the scope of the project. Some principles can guide the selection of the criteria:

1. Systemic principle: the criteria should represent the whole performance of the energy system, in all its characteristics.
2. Consistency principle: the criteria should be consistent with the objectives of the decision-making process.
3. Independency principle: the criteria should not have inclusion relationship, avoiding double-counting.
4. Measurability principle: the criteria should be measurable or quantitatively expressed.
5. Comparability principle: the criteria should be easily and clearly comparable.

The main selection methods are listed by (Wang *et al.*, 2009), while (Santoyo-Castelazo and Azapagic, 2014) argue that the integration of the sustainability indicators was carried out in most studies, using methods such as multi attribute value theory, analytical hierarchy process and weighted sum.

(Buchmayr *et al.*, 2021) built up a sustainability assessment framework, starting with the definition of the energy supply life cycle and system boundaries, and identified 12 impact categories of energy supply technologies in the three dimensions of sustainability (Figure 13), distinguishing the lifecycle phase of impact and emphasizing a spatial differentiation of impacts. For instance, while the *emission* *damage to ecosystem quality* index impacts energy supply during the whole technology lifecycle, the *quality of residential life* index impacts only the plants installation and operation stages; moreover, the *human rights* index has a local impact in non-European countries, at the resources' extraction stage.

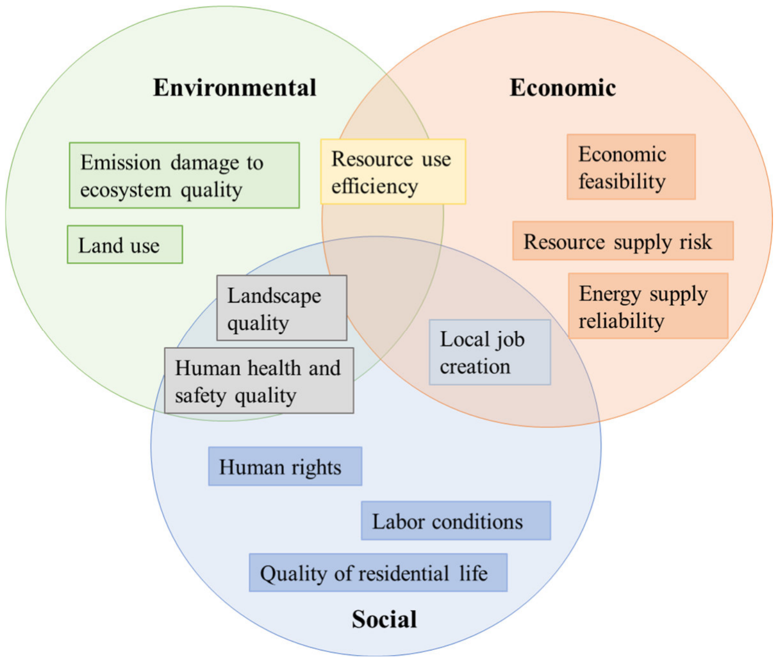


*Figure 13. Impact categories of energy supply technologies in the three dimensions of sustainability as defined in (Buchmayr et al., 2021).*

With a specific focus on renewable energy, (Liu, 2014) developed a general sustainability indicator for RES aggregating 10 basic sustainability indicators. The selected basic indicators reflect the impacts of renewable energy supply systems on the three dimensions of sustainability:

- Environmental indicators consider *GHG ($CO_2$, $NO_x$, $SO_2$) emissions*, *different renewable technologies* fraction in the energy mix, and *energy efficiency* (the ratio between the useful output of an energy conversion machine and energy consumption per person (per capita or per year) or energy consumption per dollar of gross domestic product).
- Economic indicators include *costs*, *return on investment*, and *payback period*.
- Social indicators consider *job creation* and *benefited residents*.

## 4.2 Distributed Energy Resources and systems – Sustainability Criteria

The transition from a centralized energy generation system to a distributed one requires a change in the design and management approach, concerning a complex multidimensional system. In addition, the need for a more sustainability-oriented design of distributed energy systems, considering all the three sustainability domains as objectives, is discussed by (Z. Wang *et al.*, 2019).

Generally speaking, the environmental sustainability of an energy generation plant is a key requirement, mostly at local level: the distributed configuration and the chosen RES technology affect the environmental impacts. The economic sustainability assessment must allow the local communities and energy stakeholders to pursue economic growth collectively and satisfy essential needs. The social sustainability pertains equality and basic necessities fulfillment as well as social progress of the involved community.

In this section, a comprehensive set of criteria covering all the three key sustainability dimensions of the DER scheme is presented. The criteria have been collected analyzing the literature in the period 2010-2018. The starting year 2010 was chosen because it represented a turning point in renewable technologies uptake, when the technological advancements, the declining prices of renewable energy technologies and the fast growing of the renewables installed capacity, oriented the studies on energy transition pathways to a high share of renewables to distributed configuration.

In the analysed literature (for the complete analysis see (Butturi, M.A., Lolli, F., Balugani, E., Gamberini, R., Rimini, 2018)), a great effort is committed to techno-economic optimal planning of distributed renewable energy generation in terms of choosing the best technology alternative (or technologies combination) (e.g. (Yuan *et al.*, 2018)), optimal size, location and power factor of the generation units, aiming at maximizing DER penetration and costs savings (Tanwar and Khatod, 2017). Only in (Lima *et al.*, 2018), among the reviewed papers, list a set of criteria created putting in relation the relevant characteristics of distributed generation to sustainability indicators, identifying the interconnection factors; here the assumed DER relevant characteristics are:
• Use of energy resource available on site
• Electricity production near consumption centers
• Availability of electricity to supply local demand
• Use of smaller generation units

The collected criteria (Table 14a and Table 14b) are both quantitative and qualitative. In the Table 14a, the economic criteria are listed (the technical aspects are included in the economic dimensions since they are evaluated as costs or can be easily converted in associated costs). The Table 14b presents the environmental and social criteria.

| Sustainability pillar | Criterion | Description |
|---|---|---|
| Economic (techno-economic) | Net Present Value (NPV) | Each cash inflow/outflow is discounted back to its present value. |
| | Capital and variable (O&M) costs | Capital costs and the operating and maintenance (O&M) costs, that include the project investment (mechanical equipment and electrical connections, technological and infrastructure installation, engineering services), the cash flows and the variable costs during plant running (including the salaries of operators involved in maintenance operations). |
| | Reduction of network connection costs/ distance to user | The distance to the main distribution grid and the related connection costs have great relevance in the cost of implementation of the generation unit. |
| | Conventional fuel savings | The total quantity of fossil fuels replaced by electricity generation by RES can be calculated. |
| | Payback period | The period of time required for the return of an investment to repay the sum of the initial investment, depends on the chosen renewable technology (and on the availability and density of the source of energy), storage and demand management options. |
| | Service life | It is the expected operating period of time during which the plant will produce energy (or the acceptable period of use in service) and depends on the chosen technologies. |
| | Electricity costs | Electricity costs, in terms of LCOE, depends on the chosen renewable technology. |
| | Availability and density of the source of energy | Availability and density of the source of energy (sun radiation, wind speed, …): it influences the choice of the proper RES technology. |
| | Technology efficiency | It rates how much useful energy can be obtained given the availability and density of the source of energy, and it determines the electricity generation cost. |
| | Innovation | Innovation potential of the project in terms of patents developed and potential market (i.e. new chain of energy businesses); alternatively evaluated under the social pillar. |

*Table 14a. List of sustainability related criteria (economic) from reviewed literature. The technical aspects are included in the economic dimensions since they are evaluated as costs or can be easily converted in associated costs.*

| Sustainability pillar | Criterion | Description |
|---|---|---|
| Environmental | Pollution (air – $CO_2$, $NO_x$, $SO_2$, PM10-PM2.5 emissions, noise), odours | GHG emissions (e.g. carbon dioxide) causing global warming and other pollutants hazardous to the health are considered (nitrogen oxides, sulphur dioxide and particulate matter).<br>Smells and noise can influence people's work and life. |
| | Land use | It is the area occupied by the generation unit. The DER configuration allows a substantial reduction of land use respect to centralized plants (also reducing the economic impact); when dealing with biomass (i.e. crops, wood), the competition with land used for food should be considered. |
| | Impact on landscape | Visual impact is relevant also for small energy generation units that can be located in picturesque urban or natural spaces. |
| | Impact on ecosystems | Though water consumption of distributed RES is generally low, the quality of water can be impacted, both in terms of temperature variation and contamination, in hydro power, geothermal, biomass facilities; biodiversity can also be negatively impacted by habitat disturbance and/or wildlife activity disruption: wind turbines can interfere with bird migration paths, hydro power can disrupt fish habitat, and biomass use can reduce the organics matter returned to soil. |
| | Need of waste disposal | It refers to some RES such as biomass. |
| | Physiological effects | (Hartmann *et al.*, 2017) consider "physiological effects", namely the lost years per generated energy (evaluated in [c€/kWh]), as human health indicator and include it under environmental aspects. |
| Social | Social acceptance | It expresses the overview of opinions related to the energy systems: the local character of DES projects makes essential a favourable reception from the local communities. |
| | Job creation | Energy supply systems employ people during their life cycle. |
| | Sufficient supply to meet basic needs | This criterion draws attention to the need for equitable energy availability, to promote socioeconomic development and quality of life. |
| | Social benefits | It represents local development determined by the energy project (new chain of energy businesses, new industrial regions, etc.; it can include job creation, if not make explicit); the savings allowed by the new energy system (i.e. euros saved per household/firm per year) are considered by some authors. |
| | Improvement of educational level | The improvement of educational level of the community where DES is installed is foreseen, due to the need for skilled professionals to be engaged in installation and O&M tasks that should entail local workers training. |
| | Safeguards | It expresses whether the system is safe to surrounding and people or not. |
| | Advanced performance | It expresses whether the system or technology is advanced now and will be more perfect in the future. |

*Table 14b. List of sustainability related criteria (environmental and social) from reviewed literature.*

From the literature review environmental impacts result mainly evaluated through air pollution (in the 80.4% of the reviewed papers) while local ecosystems (44.6%) and landscape (32.1%) integrity, and human health safeguard (17.9%) are often arguably implicitly included in pollution effects. Among the economic criteria, the most considered criterion is the cost of project investment and O&M (62.5%); the local availability of the source of energy is considered only by the 37.5% of the authors. Social impacts on local communities are mainly evaluated through job creation (55%), but also social acceptance and social benefits are considered important indicators (44.6%); all other social criteria are considered by less than the 18% of the papers.

# 5 SUSTAINABILITY IN ENERGY SYMBIOSIS

Energy-based symbiosis projects mainly aim at improving energy resources utilization efficiency and reducing industry carbon footprint. Usually, in the literature, the analysis of the sustainability aspects of industrial energy symbiosis is included in the wider analysis of the IS projects. As pointed out in the section 1 of this chapter, sustainability-related key performance indicators are set by national programs supporting EIPs development and, generally speaking, the assessment of the sustainability of the EIP projects is often evaluated by LCA methods and material flow analysis (Martin and Harris, 2018). On the other hand, many sustainability-related objectives are used in decision-making and decision-support analysis in the field of energy projects within eco-industrial parks.

## 5.1 SUSTAINABILITY OF EIPS

An overview of the sustainability criteria that can be considered for the assessment of the EIPs is provided by (Valenzuela-Venegas, Salgado and Díaz-Alvarado, 2016).

The indicators have been selected to capture the main characteristics of an EIP, to support decisions regarding its configurations, and to compare it with previous configurations or other parks. The analysis of indicators was performed in a process-oriented view, since the since the performance of an EIP mainly depends on the involved operations and connections.

In relation to energy, the most relevant factors considered are the input/output flows. The set of indicators for assessing the sustainability of eco-industrial parks in terms of energy are presented in the Table 15, categorized in as energy efficiency, emission-related, energy consumption related and resources use-related indicators (including energy).

| Category | Indicator | Definition | Sustainability dimension |
|---|---|---|---|
| Energy efficiency related indicators | Energy consumption per unit | The energy efficiency of the candidate enterprise by calculating of all the energy and converting to the number of standard coal using means conversion coefficients | En |
| | 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 |
| Emissions 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 of park energy productivity | The growth rate of energy production in the park after the introduction of a new business | En |
| | 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 15. The main energy related indicators used in the literature for the sustainability assessment of EIPs (adapted from (Valenzuela-Venegas, Salgado and Díaz-Alvarado, 2016)). (En=Environmental; Ec=Economic)*

As far as concern the choice of sustainability criteria to support decision making in energy projects within EIPs, the indicators set are extracted from the wider set of sustainability criteria related to energy supply and infrastructure.

For instance, the sustainability evaluation of the selection of a multi-energy system for an industrial park is investigated by (Wen *et al.*, 2021). The compared supply systems include, in various combinations, combined cooling, heating and power (CCHP), ground source heat pumps and water source heat pumps. On this basis, the authors performed selection from a dataset of criteria collected from literature and propose an evaluation criteria system including 17 indicators (Table 16).

| **Sustainability dimension** | **Criteria** | **to be …** |
|---|---|---|
| (Technical) | Primary energy utilization efficiency | maximized |
| | Exergy efficiency | maximized |
| | Maturity | maximized |
| | Reliability | maximized |
| Economic | Initial investment | minimized |
| | O&M cost | minimized |
| | Fuel purchase cost | minimized |
| | Payback period | minimized |
| Environmental | $CO_2$ emissions | minimized |
| | Nitrogen oxides emissions | minimized |
| | $SO_2$ emissions | minimized |
| | PM10 | minimized |
| | Noise | minimized |
| Social | Social acceptability | maximized |
| | Job creation | maximized |
| | Footprint (land use) | minimized |
| | Compatibility with political framework | maximized |

*Table 16. The criteria system as elaborated in (Wen et al., 2021).*

The techno-economic criteria evaluate the economic convenience of the systems installation for the firms located within the park; the environmental and social criteria extend the benefits evaluation to the surrounding area.

## 5.1 A SUSTAINABILITY CRITERIA SYSTEM FOR INDUSTRIAL ENERGY SYMBIOSIS INTEGRATING RES WITHIN EIPS

Considering the main characteristics of the industrial energy symbiosis integrating RES, a more focused sustainability criteria framework is proposed in this thesis (Table 17).

Four characteristics distinguish the energy symbiosis approach:

- the energy sources: the energy sources are no longer determined by the national energy mix. The local transition to the low carbon energy must be balanced in terms of economic convenience and emissions reduction.
- the energy conversion technologies and infrastructure: the energy symbiosis approach within EIPs considers the energy hub configuration and/or the distributed configuration integrating multi-energy systems and storage devices; demand side and smart grid management could be considered; moreover, energy exchanges can be activated between firms. The new

technologies and connections must be economically sustainable, guarantee low environmental impacts over the whole lifecycle and social acceptance.

- the energy strategies and business models: different energy strategies and business models can characterize industrial energy symbiosis projects including renewable energy technologies. The installation of new technologies can require external expertise and financing both in the investment and operating phase; different options can be evaluated impacting both the long term economic (investment and operating phase) and social sustainability of the project.
- the consequences and effects on the surrounding populated areas. Generally speaking, the project can influence the quality of life of local communities, here represented by environmental and social criteria, and be influenced by the social perception of the sustainability of renewable sources and new technologies.

| | **Economic** | **Environmental** | **Social** |
|---|---|---|---|
| **Energy sources** | -Fossil fuel prices<br>-RES prices and/or availability<br>-Fossil fuel savings<br>-(Energy cost or payback time) | -Emissions<br>-Environmental impacts (e.g. land use for biomass) | -Social responsibility at supply side<br>-Odor (biomass/ waste) |
| **Energy conversion technologies and infrastructure** | -Renewable technologies investment cost<br>-ESS investment cost<br>-Operating phase costs (including maintenance)<br>-Network connections costs<br>-(Demand side and Smart grid management costs) | -Carbon emissions (life-cycle perspective)<br>-Footprint<br>-Pollution (air, water, noise)<br>-Impact on ecosystems<br>-Need for waste disposal | -Training and improved skills<br>-Number of utility-sharing and joint infrastructure projects<br>-Innovation (e.g. patents)<br>-Health and safety<br>-Pollution perception (noise, odors, …)<br>-Social responsibility at technologies supply side<br>-Compliance with environmental regulation |
| **Business models** | -Public-private partnership (cost benefits)<br>-Service company (cost benefits)<br>-Citizens participation in financing the project (cost benefits) | | -Community involvement |
| **Surrounding urban areas** | | -Carbon emissions<br>-Pollution<br>-Visual impact | -Health and safety<br>-Job creation<br>-Improvement of educational level<br>-Social acceptance<br>-Social benefits (e.g. new chain of energy businesses, energy bills reduction) |

*Table 17. Proposed sustainability criteria system for IES integrating RES within EIPs.*

Some of the proposed criteria, mainly the social ones, are qualitatively described and must be translated in quantitative indicators. For instance, the social benefits can be quantified as the obtained energy bills reduction or the number of new businesses created thanks to the new energy project. Moreover, some of the criteria are alternative to each other, considering a specific view.

# *Chapter 3*
# Development of a Model for Renewable Energy Symbiosis networks in Eco-Industrial parks

The EIP model enables the implementation of various energy strategies, depending on the energy demand profile of the involved firms and their willingness to cooperate. The spatial configuration of the park and the existing infrastructures facilitate the creation of energy exchange networks to share the available surplus energy, and the installation of co-financed power units. EIPs internal utility networks can be viewed as small-scale grids, and they can be developed as industrial smart micro-grids consisting of inter-connected loads and distributed energy resources including RES.

This research introduces a mathematical model to analyse the integration of RES in the energy system of an EIP. While energy symbiosis modelling, and particularly thermal energy exchanges, has been widely analysed, only few papers consider the RES integration and the electricity production and exchanges.

In this chapter, three models have been developed to analyse the possible advantages of integrating renewable technologies in an energy symbiosis network, following a stakeholders' approach. Adopting a stepwise approach, the economic advantages of involved firms and environmental sustainability are firstly considered. Then, a comprehensive model considering both the EIP collective viewpoint, and the environmental impacts is developed. The models are applied to a built-up reference case to analyse different scenarios and the environmental impacts, and to a case study.

The aim of the developed models is to support energy managers, single firm or a group of firms within EIPs and, in general, decision makers to evaluate the realization of energy synergies and projects involving RES within EIPs.

This chapter is adapted from the papers:

- *A model for renewable energy symbiosis networks in eco-industrial parks,* to be published in the proceedings of the 21st IFAC World Congress (Virtual), Berlin, Germany, July 12-17, 2020 (IFAC PapersOnLine).

- *Evaluating the environmental benefit of energy symbiosis networks in eco-industrial parks*, to be published in the proceedings of the 21st IFAC World Congress (Virtual), Berlin, Germany, July 12-17, 2020 (IFAC PapersOnLine).

- *Environmental benefits of the industrial energy symbiosis approach integrating renewable energy sources*, to be published in the proceedings of the 24th SUMMER SCHOOL FRANCESCO TURCO, September 9-11, 2020 (AIDI - Italian Association of Industrial Operations Professors).

# 1 THE MODEL DEVELOPMENT

As discussed in the chapter 2, pinch analysis and mixed integer linear programming (MILP) are the main methods used to optimize energy (mainly heat) exchange networks (Kastner, Lau and Kraft, 2015). Thus, the developed model uses the mathematical optimization through MILP, to obtain optimal energy symbiosis design, considering both economic and environmental issues. Within the existing literature usually a single-objective is used, since environmental impacts are converted into costs (e.g. cost of GHGs cleaning).

The model aims to capture the major costs and environmental impacts of energy symbiosis when RES are used to satisfy a percentage of the energy demand within EIPs, taking into account that the key objective of introducing renewable technologies is to implement a low-carbon strategy. The environmental impact considers the different energy sources and flows, with the aim of minimizing carbon emissions. The considered costs take into account the carbon emissions costs as well as the investment and operational costs of using RES trough the EIP model.

Following the models proposed by (Afshari, Farel and Peng, 2018) for the thermal energy exchanges within an industrial symbiosis framework, a multi-objective model and a stakeholders' approach are here considered. As observed by the cited authors, most existing studies address only the EIP managers' viewpoint. However, a key feature of the IS approach is that it aims at producing collective benefits. Thus, together with the single firm perspective, also the collective perspective will be analysed. Through analysing three different perspectives, the single firm point of view, the environmental optimization and EIP collective perspective, different scenarios are built up to find out useful hints.

## 1.1 MODEL ASSUMPTIONS

The general scheme of the considered energy symbiosis within the EIP is schematically represented in the Figure 14. The EIP provides a spatial boundary and it is connected to the main electricity distribution grid that can satisfy all the internal electrical energy demand. Among the EIP's participants, some firms buy the whole electricity needed to satisfy their demand (buyers), while others can deliver an amount of renewable excess energy (suppliers). In addition, the EIP organization may enable the joint installation of clean energy units (eco power plants).

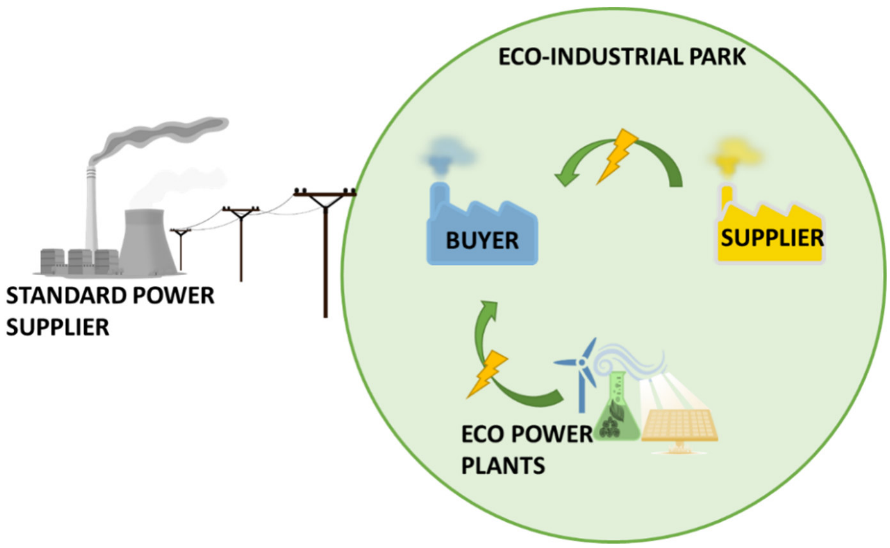


*Figure 14. General scheme of energy symbiosis within eco-industrial park, as modelled here.*

In order to formulate the optimization problem, the following general assumptions are considered:

- In the EIP, some companies equipped with renewable or low carbon energy plants, generate an energy surplus that they can supply to other companies located within the park. For instance, the energy surplus could be made available by a CHP system, supplying all the firm heat demand and a surplus of electricity. Moreover, the possibility of jointly installing renewable energy technologies is considered.
- An optimal symbiosis network, including RES, is designed for an existing cluster of industries; the scenarios resulting from the model application help decision makers and shareholders to evaluate the percentage of electricity that can be replaced using energy symbiosis to shift towards a low-carbon energy supply.
- The energy exchanges consider only electrical energy.
- The technical feasibility of the possible connections between the firms is evaluated through establishing the maximum distance of the links.
- A horizon of 10 years is considered for the cost estimation.

## 1.2 Sets, Variables and Parameters

Sets, parameters and variables of the model are listed below.

The sets include the energy suppliers (both firms with energy surplus and renewable power plants), the firms demanding energy and the time period (Table 18).

| ***SET*** | ***Description*** |
|---|---|
| I = I.Sup ∪ I.Eco | This set includes both the renewable power generation units that could be installed (I.Eco) and the firms that can supply a surplus of power (I.Sup). |
| J | Set of firms demanding energy |
| T | Set of the time period (in years) |

*Table 18. Sets of the model.*

The variables (Table 19) are both integer (1 over 5, representing electricity demand) and binary (4 over 5).

| ***VARIABLE*** | ***Description*** |
|---|---|
| $x_{ij}^t$ | Binary variable if symbiosis exists between i and j in the period t |
| $y_{ij}^t$ | Amount of the energy demand of j satisfied by i in t |
| $h_j^t$ | Binary variable if firm j achieves the energy independence (from grid) in t |
| $w_{ij}$ | Binary variable representing the investment cost if symbiosis exists between i and j |
| $z_i$ | Binary variable representing the investment cost if the eco-plant i is installed |

*Table 19. Variables of the model.*

The parameters are listed in the next Table 20.

| ***PARAMETER*** | ***Description*** |
|---|---|
| $D_j^t$ [kWh] | Energy demand of firm j in year t |
| $FD_j^t$ [€] | Fixed cost |
| $VD_j^t$[€/kWh] | Variable cost |
| $IP_j^t$ [$kgCO_2$/kWh] | Environmental impact due to standard power production |
| $RC_i^t$ [€/kWh] | Variable cost of recovering energy within firm i in year t |
| $FC_i^t$ [€] | Fixed cost of recovering energy within firm i in year t |
| $PE_i^t$ [€/kWh] | Selling price of energy from supplier firm i |
| $IC_i$ [€] | Investment cost for renewable power unit i |
| $P_i^t$ [kW] | Nominal power for unit i in period t |
| $S_i^t$ [kWh] | Energy converted by unit i in period t |
| $CM_i^t$ [€] | Fixed costs for maintenance of renewable power unit i |
| $CO_i^t$ [€/kWh] | Variable operational costs for renewable power unit i |
| $EP_i^t$ [$kgCO_2$/kWh] | Environmental impact due to renewable power production in unit $i \in I.Sup \cup I.Eco$ |
| $L_{ij}$ [km] | Distance between i and j |
| $CC_{ij}$ [€] | Investment cost for the link between i and j |
| $\gamma$ [km] | Maximum distance between i and j |
| $EC^t$ [€/$kgCO_2$] | Emission allowance cost |
| *LW* [%] | Maximum potential losses for wind energy |
| *LPV* [%] | Maximum potential losses for PV energy |
| *LB* [%] | Maximum allowed losses for biomass energy |
| *LBW* [kWh] | Loss of the biggest wind power unit |
| *LBPV* [kWh] | Loss of the biggest PV power unit |
| *LBBM* [kWh] | Loss of the biggest biomass power unit |
| $Pl^t$ [kWh] | System peak load in year t |
| $Share_r$ [%] | Amount of energy demand to be satisfied by means of renewables |
| *RM* [%] | Reserve margin of the system |
| *s* | Annual discount rate |

*Table 20. Parameters of the model.*

### 1.3 THE OBJECTIVE FUNCTIONS

Three objective functions are considered, to analyse how different perspectives can change the optimised scenarios. The first aims at minimizing the total costs of buying energy for each buyer firm; the second analyses the overall environmental impact; finally, the third provides the collective point of view, considering both the energy buyers and suppliers and simultaneously models the cost and the environmental impact.

#### 1.3.1 Individual firm viewpoint

The first objective function (1) aims at minimizing the total costs of buying energy for each individual firm, considering the entire period T.

The blocks represent:

- the sum of fixed and variable costs of the amount of non-renewable (standard) electricity bought from the grid;
- the costs of the amount of renewable energy supplied by supplier firms ($i \in I.Sup$);
- the $CO_2$ emissions allowances due to buying only standard energy;
- the cost actualization.

This objective function does not consider the costs of new energy plants installation since this point of view does not include the "collective" perspective. So, only the energy exchanges are considered.

$$\min Z_1 = \sum_{t \in T}\left\{\sum_{j \in J}\left[FD_j^t\left(1-h_j^t\right)+VD_j^t D_j^t\left(1-\sum_{i \in I} y_{ij}^t\right)+\sum_{i \in I.Sup} PE_i^t D_j^t y_{ij}^t + EC^t IP_j^t D_j^t\left(1-\sum_{i \in I} y_{ij}^t\right)\right]\right\}(1+s)^{-t} \quad (1)$$

#### 1.3.2 Environmental viewpoint

The second objective function (2) considers the environmental impact and aims at minimizing the whole carbon emissions due to the energy conversion technologies and connections.

The blocks represent:

- the emissions due to the external power generation (indirect emissions due to buying energy from the grid) and
- the emissions due to power generation respectively by supplier firms and renewable plants within the park.

$$\min \boldsymbol{Z_2} = \sum_{t \in T}\sum_{j \in J}\left[IP_j^t D_j^t\left(1-\sum_{i \in I} y_{ij}^t\right)+D_j^t \sum_{i \in I.Sup} EP_i^t y_{ij}^t + \sum_{i \in I.Eco} EP_i^t S_i^t x_{ij}^t\right] \quad (2)$$

#### 1.3.3 Collective (EIP) viewpoint

The third objective function (3) considers the optimization of both the costs and the environmental impact from a collective point of view, analysing at the same time the buyers' and the suppliers' benefits.

The blocks represent:

- the sum of fixed and variable costs of the amount of energy supplied by the grid (fossil fueled plants);
- the costs of the amount renewable energy delivered by supplier firms including the recovery costs;
- the fixed and variable costs for the installation of new clean power plants;
- the $CO_2$ emissions allowance due to the standard energy and the exchanged energy;
- the cost of the investments for the new plants and the connections;
- the costs actualization.

$$\begin{aligned}\mathbf{min}Z_3 = \sum_{t\in T}\Bigg\{&\sum_{j\in J}\left[FD_j^t(1-h_j^t)+VD_j^tD_j^t\left(1-\sum_{i\in I}y_{ij}^t\right)\right]+\sum_{j\in J}\sum_{i\in I.Sup}(FC_i^tx_{ij}^t+RC_i^tD_j^ty_{ij}^t)+\\&+\sum_{i\in I.Eco}\left(CM_i^tz_i+\sum_{j\in J}CO_i^tD_j^ty_{ij}^t\right)+\\&+\sum_{j\in J}\left[EC^tIP_j^tD_j^t(1-y_{ij}^t)-EC^t\sum_{i\in I.Sup}EP_i^tD_j^ty_{ij}^t+EC^t\sum_{i\in I.Eco}EP_i^t(S_i^t-D_j^ty_{ij}^t)\right]\Bigg\}(1+s)^{-t}+\\&+\sum_{i\in I.Eco}IC_iz_i+\sum_{j\in J}\sum_{i\in I}CC_{ij}w_{ij}\end{aligned} \quad (3)$$

The three perspectives are outlined in the next Figure 15.

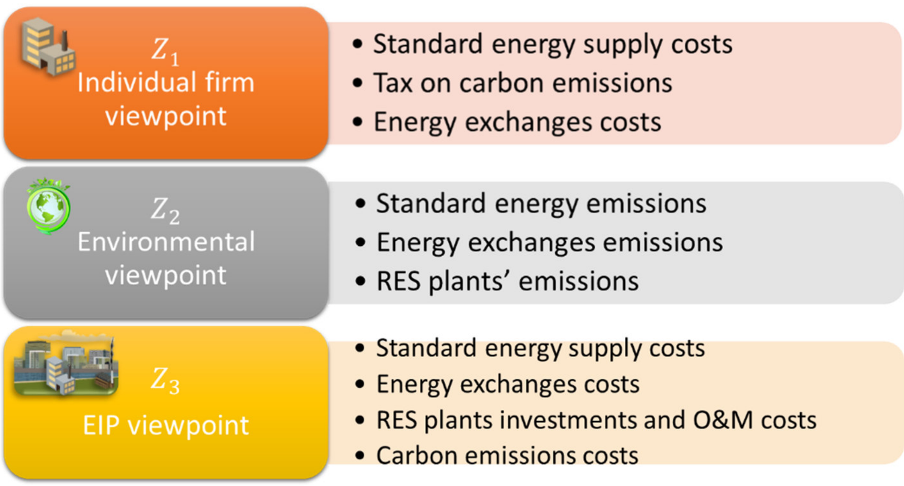


*Figure 15. Comparison of the main purposes of the models.*

### 1.3.4 The constraints of the model

The constraints of the model can be grouped as variables' related, technical, economic and related to energy management.

The first group of constraints (4) to (8) defines the variables type in the model.

$$x_{ij}^t \in \{0,1\} \quad \forall\ t,i,j \tag{4}$$

$$0 \leq y_{ij}^t \leq 1 \quad \forall\ t,i,j \tag{5}$$

$$z_i \in \{0,1\} \quad \forall\, i \in I.Eco \tag{6}$$

$$w_{ij} \in \{0,1\} \quad \forall\, i,j \tag{7}$$

$$h_j^t \in \{0,1\} \quad \forall\, t,j \tag{8}$$

Constraint (9) refers to satisfy up to the whole buyers' energy demand.

$$\sum_{i \in I} y_{ij}^t \leq 1 \quad \forall\ t,j \tag{9}$$

Constraint (10) guarantees that if symbioses are working an amount of energy demand is satisfied; similarly, constraint (11) guarantees that an eco-plant is operating only if there is energy demand, and constraint (12) guarantees that the costs of existing symbioses are considered.

$$y_{ij}^t \leq x_{ij}^t \quad \forall\ t,i,j \tag{10}$$

$$\sum_{t \in T} \sum_{j \in J} x_{ij}^t \geq z_i \quad \forall\ i \in I.Eco \tag{11}$$

$$\sum_{t \in T} x_{ij}^t \geq w_{ij} \quad \forall\, i,j \tag{12}$$

Constraint (13) verify the energy independence from the grid of a buyer firm.

$$h_j^t \leq \sum_{i \in I} y_{ij}^t \quad \forall\ t,j \tag{13}$$

Constraint (14) defines the geographical limits of the park dictating a maximum distance between buyer and supplier.

$$\left(L_{ij} w_{ij} - \gamma\right) \leq 0 \quad \forall\ i,j \tag{14}$$

The next group of constraints manages the relation between demand and supply. Constraint (15) guarantees that suppliers can provide excess energy to support the exchanges and constraint (16) controls that the energy supplied does not exceed the surplus availability.

$$D_i^j y_{ij}^t \leq S_i^t x_{ij}^t \quad \forall\ t,i,j \tag{15}$$

$$\sum_{j \in J} D_j^t y_{ij}^t \leq S_i^j \quad \forall \ t, j \tag{16}$$

Constraints (17) and (18) dictate the economic sustainability of the symbioses for the buyers and suppliers respectively, while constraint (19) dictates the economic sustainability from the collective point of view.

$$\begin{aligned} FD_j^t + VD_j^t D_j^t \sum_{i \in I.Sup} y_{ij}^t + IP_j^t D_j^t EC^t \sum_{i \in I.Sup} y_{ij}^t \\ \geq \sum_{i \in I.Sup} \left[ \left( PE_i^t - EC^t IP_j^T \right) D_j^t y_{ij}^t \right] \quad \forall \ t, j \end{aligned} \tag{17}$$

$$\sum_{j \in J} PE_i^t D_j^t y_{ij}^t \geq \sum_{j \in J} RC_i^t D_j^t y_{ij}^t + \sum_{j \in J} FC_i^t x_{ij}^t - \sum_{j \in J} EC^t EP_i^t D_j^t y_{ij}^t \quad \forall \ t, i \in I \tag{18}$$

$$\begin{aligned} \sum_{t \in T} \left[ \sum_{j \in J} \left( FD_j^t + VD_j^t D_j^t \sum_{i \in I.Eco} y_{ij}^t + EC^t IP_j^t D_j^t \sum_{i \in I.Eco} y_{ij}^t \right) \right] (1+s)^{-t} \\ \geq \sum_{t \in T} \left\{ \sum_{i \in I.Eco} \left[ CM_i^t z_i + CO_i^t \sum_{j \in J} D_j^t y_{ij}^t \right] \right\} (1+s)^{-t} + \sum_{j \in J} \sum_{i \in I} CC_{ij} w_{ij} + \\ + \sum_{i \in I.Eco} IC_i z_i \end{aligned} \tag{19}$$

Constraint (20) ensures the availability of the demanded energy even if fluctuations in the supply occur.

$$\begin{aligned} RM \sum_{t \in T} \sum_{i \in I} S_i^t x_{ij}^t \\ \leq \sum_{t \in T} \sum_{i \in I} S_i^t x_{ij}^t - LW \sum_{t \in T} \sum_{i \in I.Wind} S_i^t x_{ij}^t - LPV \sum_{t \in T} \sum_{i \in I.PV} S_i^t x_{ij}^t + \\ - LB \sum_{t \in T} \sum_{i \in I.Bio} S_i^t x_{ij}^t - LBW - LBPV - LBBM - PI^t \quad \forall \ t \end{aligned} \tag{20}$$

Constraint (21) controls the possibility of introducing a minimum share of renewable energy.

$$\sum_{j \in J} \sum_{i \in I} D_j^t y_{ij}^t \geq Share_r \sum_{j \in J} D_j^t \quad \forall \ t \tag{21}$$

Constraints (20) and (21) have been developed according to the observations of (Pereira, Ferreira and Vaz, 2016), that analyse how to model the integration of RES within the power grid of Portugal.

The next Figure 16 summarizes the constraints' scope:

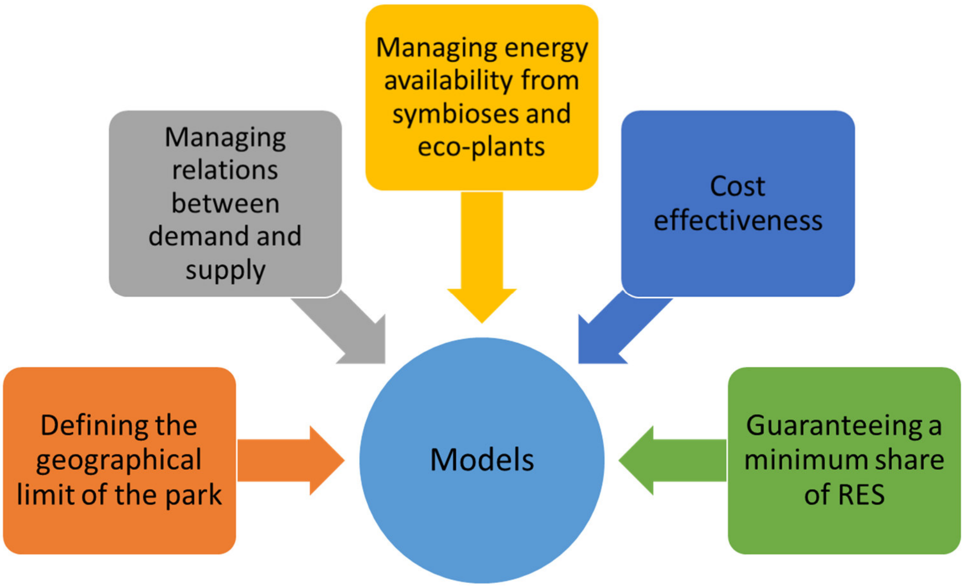


*Figure 16. Constraints of the model scope.*

# 2 MODEL APPLICATION

Firstly, to test the model, and ensure the complete availability of data, a representative industrial park has been built hypothesizing the possibility of creating both electricity exchanges and joint renewable energy plants.

## 2.1 THE REFERENCE CASE

The created reference EIP consists of 9 firms, including three potential energy suppliers (S1 to S3), while 6 firms are the energy buyers (B1 to B6). According to the possible energy symbiosis schemes discussed in the chapter 2, we consider also the possibility of installing collectively some differently sized eco-plants: three biomass plants (M1 to M3), three wind plants (W1 to W3) and three photovoltaic (PV) plants (P1 to P3). A picture of the reference EIP is given in the next Figure 17.

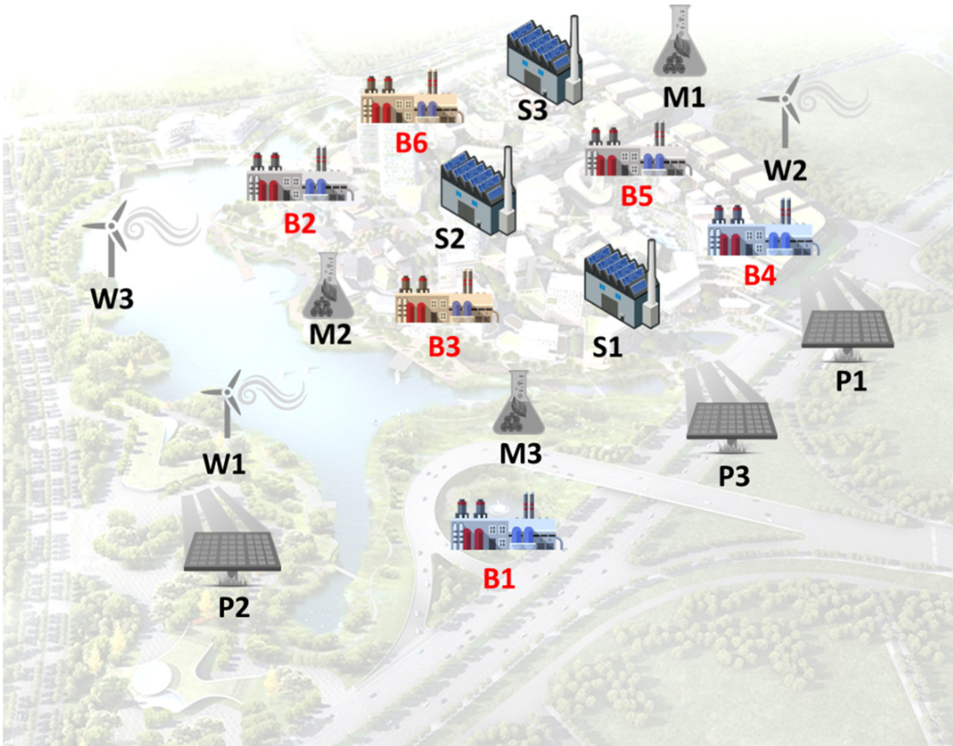


*Figure 17. Spatial representation of the reference EIP: the buyer firms are red marked, while supplier firms' roofs host PV plants supplying electricity in excess respect to supplier firms demand; the eco-plants (all in grey) are only hypothetical at the initial stage.*

### 2.1.1 Reference case data

The graphic representation of the reference EIP shows the approximate location of the facilities. The Euclidean distances between facilities are shown in the Table 21, while according to (Afshari, Farel and Peng, 2018), the maximum distance between two connected facilities is $\gamma = 20$ km to avoid high costs for the connection infrastructures.

| Distance $L_{ij}$ (km) | Buyers | | | | | | |
|---|---|---|---|---|---|---|---|
| | | **B1** | **B2** | **B3** | **B4** | **B5** | **B6** |
| Suppliers | S1 | 6 | 13 | 3 | 6 | 4 | 6 |
| | S2 | 17 | 3 | 8 | 8 | 6 | 4 |
| | S3 | 8 | 6 | 6 | 4 | 4 | 4 |
| Wind | W1 | 9 | 2 | 9 | 8 | 7 | 6 |
| | W2 | 6 | 8 | 11 | 13 | 9 | 7 |
| | W3 | 3 | 7 | 6 | 8 | 4 | 3 |
| PV | P1 | 4 | 13 | 4 | 8 | 4 | 6 |
| | P2 | 8 | 12 | 3 | 3 | 6 | 6 |
| | P3 | 7 | 4 | 11 | 11 | 15 | 6 |
| Biomass | M1 | 4 | 6 | 10 | 10 | 6 | 4 |
| | M2 | 8 | 8 | 2 | 2 | 4 | 4 |
| | M3 | 8 | 4 | 6 | 6 | 6 | 4 |

*Table 21. Euclidean distance between facilities.*

Three energy consumption profiles have been chosen for the energy buyers, considering high (range 1000 MWh/year), medium (range 100 MWh/year) and small (range 10 MWh/year) industry energy consumers according to (Cialani and Mortazavi, 2018). The annual demand and the fixed and variable cost for the buyers are in Table 22.

| | Year | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| $D^t_j$ | Annual demand (x 100 MWh) | | | | | | | | | |
| B1 | 30 | 30 | 30 | 40 | 40 | 30 | 30 | 30 | 40 | 30 |
| B2 | 6 | 5 | 5 | 6 | 6 | 5 | 5 | 6 | 5 | 5 |
| B3 | 0,2 | 0,3 | 0,1 | 0,3 | 0,3 | 0,3 | 0,2 | 0,3 | 0,1 | 0,2 |
| B4 | 30 | 30 | 40 | 30 | 40 | 40 | 40 | 30 | 30 | 40 |
| B5 | 5 | 6 | 6 | 5 | 6 | 6 | 6 | 6 | 6 | 5 |
| B6 | 0,3 | 0,1 | 0,2 | 0,2 | 0,1 | 0,1 | 0,2 | 0,2 | 0,3 | 0,3 |
| $FD^t_j$ | Fixed costs (x1000€) | | | | | | | | | |
| B1 | 149 | 149 | 149 | 198 | 198 | 149 | 149 | 149 | 198 | 149 |
| B2 | 30 | 25 | 25 | 30 | 30 | 25 | 25 | 30 | 25 | 25 |
| B3 | 1 | 1 | 0 | 1 | 1 | 1 | 1 | 1 | 0 | 1 |
| B4 | 149 | 149 | 198 | 149 | 198 | 198 | 198 | 149 | 149 | 198 |
| B5 | 25 | 30 | 30 | 25 | 30 | 30 | 30 | 30 | 30 | 25 |
| B6 | 1 | 0 | 1 | 1 | 0 | 0 | 1 | 1 | 1 | 1 |
| $VD^t_j$ | Variable costs (€/kWh) | | | | | | | | | |
| B1 | 0,06 | 0,06 | 0,06 | 0,06 | 0,06 | 0,06 | 0,06 | 0,06 | 0,06 | 0,06 |
| B2 | 0,08 | 0,08 | 0,08 | 0,08 | 0,08 | 0,08 | 0,08 | 0,08 | 0,08 | 0,08 |
| B3 | 0,11 | 0,11 | 0,11 | 0,11 | 0,11 | 0,11 | 0,11 | 0,11 | 0,11 | 0,11 |
| B4 | 0,06 | 0,06 | 0,06 | 0,06 | 0,06 | 0,06 | 0,06 | 0,06 | 0,06 | 0,06 |
| B5 | 0,08 | 0,08 | 0,08 | 0,08 | 0,08 | 0,08 | 0,08 | 0,08 | 0,08 | 0,08 |
| B6 | 0,11 | 0,11 | 0,11 | 0,11 | 0,11 | 0,11 | 0,11 | 0,11 | 0,11 | 0,11 |

*Table 22. Annual demand, fixed and variable costs considered for the buyers*

The maximum potential losses for wind, photovoltaics and biomass energy (*LW, LPV, LB*) have been calculated from published data on electric energy productivity (Terna Spa, 2018). The percentage of the energy demand to be satisfied by means of renewables have been agreed according to the "2030 Climate & Energy Framework" of the European Union (European Commission, 2014). The complete set of parameters is presented in the Table 23.

| Parameter | Value |
|---|---|
| Maximum distance (L) | 20 km |
| *Share$_r$* | 0,4% |
| RM | 0,3% |
| Discount rate | 0,4% |
| LW | 0,4% |
| LPV | 0,3% |
| LB | 0,4% |
| $EC^t$ | [26-28] €/$10^3 kgCO_2$ |
| $IP_j^t$ | 0,702 $kgCO_2/kWh$ |

*Table 23. Parameters.*

The energy supplied by the grid (standard power suppliers) is considered all produced by fossil fuels; when applied to real case studies the local energy mix should be considered. The time range for the optimization (T) covers 10 years. The energy suppliers can provide an energy surplus in the range of thousands kWh/year, calculated as the 1% of the annual consumption of a medium firm (Table 24).

| | Year | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| $S^t_i$ | Annual supply (x 100 kWh) | | | | | | | | | |
| S1 | 70 | 60 | 60 | 50 | 80 | 60 | 50 | 50 | 80 | 50 |
| S2 | 50 | 70 | 60 | 70 | 60 | 70 | 60 | 80 | 50 | 80 |
| S3 | 50 | 70 | 50 | 60 | 80 | 80 | 70 | 70 | 50 | 60 |
| $FC^t_i$ | Fixed costs (x100k€) | | | | | | | | | |
| S1 | 28 | 24 | 24 | 20 | 32 | 24 | 20 | 20 | 32 | 20 |
| S2 | 20 | 28 | 24 | 28 | 24 | 28 | 24 | 32 | 20 | 32 |
| S3 | 20 | 28 | 20 | 24 | 32 | 32 | 28 | 28 | 20 | 24 |
| $RC^t_i$ | Variable costs (€/kWh) | | | | | | | | | |
| S1 | 0,30 | 0,20 | 0,30 | 0,30 | 0,20 | 0,20 | 0,20 | 0,20 | 0,20 | 0,30 |
| S2 | 0,30 | 0,30 | 0,20 | 0,20 | 0,30 | 0,20 | 0,30 | 0,30 | 0,20 | 0,30 |
| S3 | 0,30 | 0,20 | 0,20 | 0,20 | 0,20 | 0,30 | 0,20 | 0,20 | 0,20 | 0,30 |
| $PE^t_i$ | Energy unitary price (€/kWh) | | | | | | | | | |
| S1 | 0,40 | 0,50 | 0,50 | 0,40 | 0,60 | 0,50 | 0,40 | 0,40 | 0,40 | 0,60 |
| S2 | 0,40 | 0,60 | 0,50 | 0,50 | 0,40 | 0,60 | 0,60 | 0,60 | 0,60 | 0,40 |
| S3 | 0,50 | 0,60 | 0,40 | 0,60 | 0,40 | 0,40 | 0,60 | 0,50 | 0,60 | 0,60 |
| $EP^t_i$ | Carbon emissions ($kgCO_2/kWh$) | | | | | | | | | |
| S1 | 0,2 | 0,2 | 0,2 | 0,2 | 0,2 | 0,2 | 0,2 | 0,2 | 0,2 | 0,2 |
| S2 | 0,2 | 0,2 | 0,2 | 0,2 | 0,2 | 0,2 | 0,2 | 0,2 | 0,2 | 0,2 |
| S3 | 0,2 | 0,2 | 0,2 | 0,2 | 0,2 | 0,2 | 0,2 | 0,2 | 0,2 | 0,2 |

*Table 24. Annual energy surplus, fixed and variable costs, energy price and carbon emissions considered for the suppliers*

The techno-economics data concerning the renewable technologies plants (eco-plants) have been extrapolated from (Kost *et al.*, 2018). At this step, the eco-plants' dimensioning considers only the capacity of the energy units, since the model focus on the demand-supply mechanism. The capacity and investment costs for the eco-plants are presented in the Table 25.

| | Plant | **Capacity (kW)** | **Investment (€)** |
|---|---|---|---|
| Wind | W1 | 2000 | 3.000.000 |
| | W2 | 3000 | 4.500.000 |
| | W3 | 4000 | 6.000.000 |
| PV | P1 | 500 | 400.000 |
| | P2 | 1000 | 800.000 |
| | P3 | 2000 | 1.200.000 |
| Biomass | M1 | 600 | 1.200.000 |
| | M2 | 800 | 1.600.000 |
| | M3 | 1000 | 2.000.000 |

*Table 25. Eco-plants capacity and investment costs.*

To estimate the yearly energy production of the renewable technologies, the use of the *capacity factor* ($\phi$) allows the evaluation of the potential plant productivity with a precision reasonable for this analysis. The capacity factor represents the actual energy production divided by the maximum possible electricity output of a power plant over a period of time. It depends on the energy source availability and the conversion efficiency of the considered renewable technology. Due to the strong growth of renewables installed capacity, current mean values of $\phi$ for the installed renewable energy conversion technologies are calculated on monthly and yearly basis at regional and national level for the currently available technologies (obviously, the mean capacity factor tends to rise as technologies with improved performances are installed).

The used capacity factors, mean values extracted from (IRENA, 2018), are:

$\phi_{Wind}$ = 27 ÷ 33 %

$\phi_{PV}$ = 15 ÷ 20 %

$\phi_{Biomass}$ = 67 ÷ 74 %

The energy production $S_i^t$, over the period t, of *i-th* eco-plant can be written as a function of the capacity factor (22)(1):

$$S_i^t = P_i \cdot \phi_i \cdot (365 days) \cdot \left(24 \frac{h}{days}\right) \quad \forall\ i, j \tag{1}$$

The eco-plants data (fixed and variable costs) have been extracted from (IRENA, 2018). For simplicity, global mean values have been chosen (Table 26, Table 27, Table 28). The mean lifecycle carbon emissions for the different technologies have been extracted from (Schlömer S. *et al.*, 2014).

| | Year | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| $S^t_i$ | Annual supply (MWh) | | | | | | | | | |
| P1 | 788 | 701 | 788 | 920 | 832 | 832 | 657 | 701 | 745 | 745 |
| P2 | 1752 | 1402 | 1840 | 1489 | 1752 | 1402 | 1402 | 1664 | 1314 | 1752 |
| P3 | 2628 | 3504 | 2628 | 2803 | 3504 | 2628 | 3329 | 3154 | 3154 | 3329 |
| $CM^t_i$ | Fixed costs (x1000€) | | | | | | | | | |
| P1 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 | 4 |
| P2 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 8 |
| P3 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 | 12 |
| $CO^t_i$ | Variable costs (€/kWh) | | | | | | | | | |
| P1 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| P2 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| P3 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| $EP^t_i$ | Carbon emissions (kg$CO_2$/kWh) | | | | | | | | | |
| P1 | 0,03 | 0,03 | 0,03 | 0,03 | 0,03 | 0,03 | 0,03 | 0,03 | 0,03 | 0,03 |
| P2 | 0,05 | 0,05 | 0,05 | 0,05 | 0,05 | 0,05 | 0,05 | 0,05 | 0,05 | 0,05 |
| P3 | 0,07 | 0,07 | 0,07 | 0,07 | 0,07 | 0,07 | 0,07 | 0,07 | 0,07 | 0,07 |

*Table 26. PV plants data.*

| | Year | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| $S^t_i$ | Annual supply (MWh) | | | | | | | | | |
| W1 | 5431 | 5782 | 4730 | 5256 | 5431 | 5081 | 4906 | 5606 | 5782 | 4730 |
| W2 | 8147 | 7096 | 7884 | 7358 | 8410 | 8410 | 8410 | 8147 | 7096 | 7358 |
| W3 | 9811 | 11213 | 11563 | 9461 | 10862 | 10512 | 10862 | 10162 | 11213 | 10162 |
| $CM^t_i$ | Fixed costs (x1000€) | | | | | | | | | |
| W1 | 1358 | 1445 | 1445 | 1445 | 1445 | 1445 | 1445 | 1445 | 1445 | 1445 |
| W2 | 2037 | 1774 | 1774 | 1774 | 1774 | 1774 | 1774 | 1774 | 1774 | 1774 |
| W3 | 2453 | 2803 | 2803 | 2803 | 2803 | 2803 | 2803 | 2803 | 2803 | 2803 |
| $CO^t_i$ | Variable costs (€/kWh) | | | | | | | | | |
| W1 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| W2 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| W3 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 | 0,00 |
| $EP^t_i$ | Carbon emissions (kg$CO_2$/kWh) | | | | | | | | | |
| W1 | 0,007 | 0,007 | 0,007 | 0,007 | 0,007 | 0,007 | 0,007 | 0,007 | 0,007 | 0,007 |
| W2 | 0,007 | 0,007 | 0,007 | 0,007 | 0,007 | 0,007 | 0,007 | 0,007 | 0,007 | 0,007 |
| W3 | 0,007 | 0,007 | 0,007 | 0,007 | 0,007 | 0,007 | 0,007 | 0,007 | 0,007 | 0,007 |

*Table 27. Wind plants data.*

| | Year | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| $S^t_i$ | Annual supply (MWh) | | | | | | | | | |
| M1 | 3627 | 3784 | 3732 | 3837 | 3679 | 3522 | 3627 | 3732 | 3889 | 3574 |
| M2 | 4695 | 5116 | 5186 | 5186 | 4765 | 4836 | 5186 | 4836 | 4695 | 5186 |
| M3 | 6482 | 6220 | 5869 | 5869 | 5869 | 5957 | 6044 | 5957 | 5869 | 6220 |
| $CM^t_i$ | Fixed costs (x1000€) | | | | | | | | | |
| M1 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 | 30 |
| M2 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 |
| M3 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 | 50 |
| $CO^t_i$ | Variable costs (€/kWh) | | | | | | | | | |
| M1 | 0,69 | 0,72 | 0,71 | 0,73 | 0,70 | 0,67 | 0,69 | 0,71 | 0,74 | 0,68 |
| M2 | 0,67 | 0,73 | 0,74 | 0,74 | 0,68 | 0,69 | 0,74 | 0,69 | 0,67 | 0,74 |
| M3 | 0,74 | 0,71 | 0,67 | 0,67 | 0,67 | 0,68 | 0,69 | 0,68 | 0,67 | 0,71 |
| $EP^t_i$ | Carbon emissions (kg$CO_2$/kWh) | | | | | | | | | |
| M1 | 0,2 | 0,2 | 0,2 | 0,2 | 0,2 | 0,2 | 0,2 | 0,2 | 0,2 | 0,2 |
| M2 | 0,2 | 0,2 | 0,2 | 0,2 | 0,2 | 0,2 | 0,2 | 0,2 | 0,2 | 0,2 |
| M3 | 0,2 | 0,2 | 0,2 | 0,2 | 0,2 | 0,2 | 0,2 | 0,2 | 0,2 | 0,2 |

*Table 28. Biomass plants data.*

### 2.1.2 Modelled energy symbiosis scenarios

The developed models have been coded and elaborated using MATLAB's *Optimization Toolbox* and a *problem-based* approach, in order to manage the data in matrix form.

Each of the three models provides the optimization from its related perspective, building up three complex scenarios outlining all the energy flows among facilities (buyers, suppliers and eco-plants) per year, on the total temporal range of 10 years. The obtained results allow to compare the different viewpoints, provide some helpful information on the possible configurations of the energy symbiosis, and suggest some model improvements.

The results of the scenario 1, obtained minimizing the costs for the buyer firms, are shown in the Table 29.

| | B1 | B2 | B3 | B4 | B5 | B6 |
|---|---|---|---|---|---|---|
| S1 | 0 | 0 | 0 | 0 | 0 | 0 |
| S2 | 0 | 0 | 0 | 0 | 0 | 0 |
| S3 | 0 | 0 | 0 | 0 | 0 | 0 |
| P1 | 0,050988333 | 0,4 | 0,8 | 0,015644 | 0,232433333 | 0,9 |
| P2 | 0,13943 | 0 | 0,1 | 0,1679 | 0,2 | 0 |
| P3 | 0,303946667 | 0,2 | 0 | 0,227257 | 0,367566667 | 0,1 |
| W1 | 0,21019 | 0 | 0 | 0 | 0 | 0 |
| W3 | 0 | 0 | 0 | 0 | 0 | 0 |
| M1 | 0,195445 | 0,1 | 0 | 0,2614176 | 0 | 0 |
| M2 | 0,1 | 0 | 0 | 0,04678 | 0 | 0 |
| M3 | 0 | 0,3 | 0,1 | 0,2810014 | 0,2 | 0 |
| W3 | 0 | 0 | 0 | 0 | 0 | 0 |

*Table 29. Yearly share of electricity supplied to buyer firms by eco-plants in scenario 1.*

As can be seen in the table, in the scenario 1 each buyer company, weighed equally in the optimization, is entirely fed by the eco-plants. It should be noted that this scenario should be applicable if a service company would take on investment and operation and maintenance costs of the plants. In this case, the buyers prefer buying the energy provided by the eco-plants to the exchange with suppliers because, after returning all the investments, the energy from renewable sources would cost less in economic terms than a partner's surplus.

The next Table 30 and Table 31 present the results for scenario 2 and scenario 3, respectively.

| | B1 | B2 | B3 | B4 | B5 | B6 |
|---|---|---|---|---|---|---|
| S1 | 0 | 0,0016 | 0,043333333 | 0 | 0 | 0 |
| S2 | 0 | 0 | 0,05 | 0 | 0 | 0,0325 |
| S3 | 0 | 0 | 0,076666667 | 1,20E-04 | 0 | 0 |
| P1 | 0 | 0,0984 | 0 | 0,078602 | 0,015133333 | 0 |
| P2 | 0 | 0 | 0 | 0 | 0 | 0 |
| P3 | 0 | 0 | 0,546666667 | 0,59198 | 0,512833333 | 0,685 |
| W1 | 0,9989 | 0,803233333 | 0,2 | 0,303878 | 0,4 | 0,2 |
| W3 | 0 | 0 | 0 | 0 | 0 | 0 |
| M1 | 0 | 0 | 0 | 0 | 0 | 0 |
| M2 | 0 | 0 | 0 | 0 | 0 | 0 |
| M3 | 0 | 0 | 0 | 0 | 0 | 0 |
| W3 | 0 | 0 | 0 | 0 | 0 | 0 |

*Table 30. Yearly share of electricity supplied to buyer firms in scenario 2.*

| | B1 | B2 | B3 | B4 | B5 | B6 |
|---|---|---|---|---|---|---|
| S1 | 0 | 0 | 0,325 | 0 | 0 | 0 |
| S2 | 0 | 0,012133333 | 0 | 0 | 0 | 0 |
| S3 | 0 | 0 | 0 | 0,001505 | 0 | 0 |
| P1 | 0 | 0 | 0 | 0 | 0 | 0 |
| P2 | 0 | 0 | 0 | 0 | 0 | 0 |
| P3 | 0 | 0 | 0 | 0 | 0 | 0 |
| W1 | 0 | 0 | 0 | 0 | 0 | 0 |
| W3 | 0 | 0 | 0 | 0 | 0 | 0 |
| M1 | 0 | 0 | 0 | 0 | 0 | 0 |
| M2 | 0 | 0 | 0 | 0 | 0 | 0 |
| M3 | 1 | 0 | 0,675 | 0 | 1 | 0 |
| W3 | 0 | 0,987866667 | 0 | 0,998495 | 0 | 1 |

*Table 31. Yearly share of electricity supplied to buyer firms in scenario 3.*

Both in the scenarios 1 and 3 (concerning the collective perspective) the energy demand is fully satisfied by the facilities inside the park. In the scenario 3, that considers any cost and savings of both buyers and suppliers, the inter-firm exchanges result to be the most economic choice. Overall, in the scenario 1 all the PV and biomass units should be opened and one wind power plant; in the scenario 2, two PV plants and one wind plant are opened; in the scenario 3 only two biomass plants are opened. In the scenario 2, that minimises carbon emissions, the extension of the links increases to more than 260 km, since the minimization of environmental impacts does not include the minimization of infrastructure costs.

Clearly, the scenario 3 manages more effectively the energy exchanges and the eco-plants chosen to be part of the park. Supplier companies provide all their excess energy and the opened eco-plants more than 70% of their power production.

A more representative picture of the results is given in the Figure 18. The advantageous energy connections for the buyer B3 in the three different scenarios are shown. The average amount of the energy demand satisfied over the entire period T, is shown in percentage.

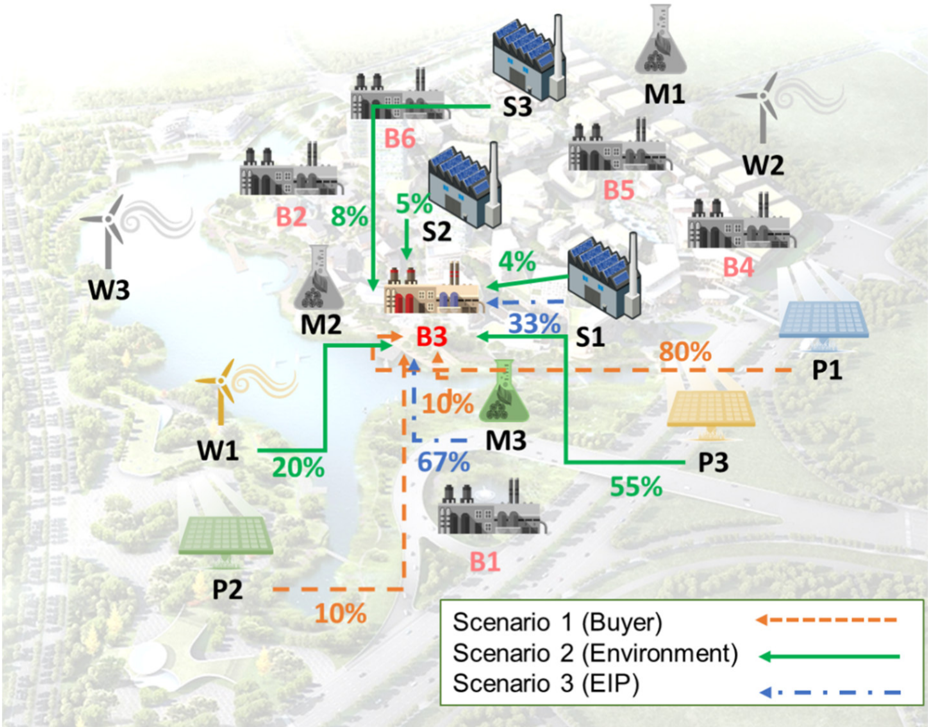


*Figure 18. Energy connections to B3 in the three scenarios resulting from corresponding objective functions minimization.*

In the scenario 1 (orange dotted lines) the energy demand of the buyer B3 results entirely satisfied by two PV plants and a biomass plant. The scenario 2, that minimizes the environmental impacts (green lines), shows the activation of energy flows between B3 and two different renewable technologies units (PV and wind). It should be noted that, according to IPCC (Bruckner *et al.*, 2014), the life-cycle emissions for the eco-plants have been considered, so in the calculation the carbon emissions of PV and wind systems are not null. In addition, energy symbioses between the buyer B3 and the suppliers are activated. S1, S2, and S3 supply altogether the 17% of the buyer energy demand.

The scenario 3 is the collective scenario (blue dotted lines); it acts balancing the needs of all stakeholders. As expected, it enables the activation of energy symbiosis between the buyer B3 and the supplier S1, that supplies the 33% of the buyer energy demand. The 67% of B3 energy demand is supplied by the biomass plant M3.

Similar pictures can be traced for all the buyers.

### 2.1.3 Scenarios analysis

Further analyses of the results have been performed introducing a set of indicators consistent with the objectives of the energy symbiosis approach.

The indicators consider the whole temporal range to get the positive aspects of the long-term plan. They provide to the park and firms managers some useful information on how efficiently the resources are used calculating the percentage of surplus energy unused or employed in the exchanges, the percentage of energy converted from renewable sources and the carbon footprint reduction.

#### *2.1.3.1 Energy efficiency*

The energy efficiency is not explicitly requested in the developed model. However, it is a key objective when implementing a low-carbon strategy in energy planning.

Two energy efficiency indicators have been defined, to value the capacity of the system to exploit the available electrical energy. The greater the incidence of intra-park exchanges, the better the system logistic will become solid and resilient. These indicators show the amount of energy demand satisfied by energy exchanges or renewable plants within the park.

The indicator (23) evaluate the share of energy exchanges between buyers and suppliers.

$$ES = \sum_{t \in T} \sum_{j \in J} \sum_{i \in I.Sup} \frac{D_j^t y_{ij}^t}{S_i^t x_{ij}^t} \tag{23}$$

While the energy converted by eco-plants is evaluated in (24):

$$RE = \sum_{t \in T} \sum_{j \in J} \sum_{i \in I.Eco} \frac{D_j^t y_{ij}^t}{S_i^t x_{ij}^t} \tag{24}$$

#### *2.1.3.2 Economic convenience*

The economic convenience of the energy exchanges for suppliers can promote the oversizing of the owned renewable plant. Through the optimal solution of the three problems, it is possible calculate the variation of costs before and after the realization of the energy symbiosis projects. The percentage reduction of costs for suppliers (25) is:

$$SC = 1 - \sum_{t \in T} \sum_{i \in I.Sup} \frac{\sum_{j \in J}\left[\left(EC^t EP_j^t + PE_j^t - RC_i^t\right) \cdot D_j^t y_{ij}^t - FC_i^t x_{ij}^t\right]}{EC^t EP_i^t S_i^t x_{ij}^t} \tag{25}$$

#### *2.1.3.3 Emissions reduction*

An environmental indicator (26) has been defined to value the carbon emissions reduction in the three scenarios.

$$EI = 1 - \sum_{t \in T} \sum_{j \in J} \frac{\sum_{i \in I.Sup} EP_i^t D_j^t y_{ij}^t + \sum_{i \in I.Eco} EP_i^t D_j^t y_{ij}^t}{\sum_{i \in I} IP_j^t D_j^t y_{ij}^t} \tag{26}$$

The indicators evaluation is summarized in the Table 32.

| % | Scenario 1 | Scenario 2 | Scenario 3 |
|---|---|---|---|
| ES | 0 | 89 | 100 |
| RE | 43 | 24 | 27 |
| SC | 0 | 14 | 3 |
| EI | 83 | 96 | 72 |

*Table 32. Indicators' calculation.*

The energy exchanges are fully exploited in the framework of scenario 3, while the eco-plants use is maximized in the scenario 1 because in this scenario the investment costs are not considered. Energy surplus supply represents an economic convenience for suppliers. The costs reduction is greater in the scenario 2, since maximizing exchanges involves more infrastructure costs (though shared with buyers). A significant emissions reduction is obtained in all the scenarios, with an obvious maximum reduction in the scenario 2.

## 2.2 Analyzing the environmental impact

Preserving the environment is one of the main motivations shared by the EIPs' participants. In the literature, this shared goal leads to design optimized resources use, minimizing natural resources consumption or formulating the impacts through a life cycle approach or a water footprint approach. In the IS field the LCA approach has been widely applied, mainly to measure environmental impacts of existing systems (Kim, Ohnishi, *et al.*, 2018). According to (Boix *et al.*, 2015) the development of an environmental objective function, aiming at optimising environmental impacts, combined with the evaluation of such an impact through LCA approach (that precisely assess the impacts, but does not improve the solution), can give key information to reach environmental optimal solutions.

Thus, the results obtained by minimising the environmental objective function (2) have been compared with those obtained by the environmental assessment study conducted with the LCA methodology[15]. The modelled symbiosis scenario provides the input data for the life cycle inventory (LCI) analysis.

As seen before, the evaluation of the EI indicator (26) shows a mean carbon emission reduction of the 96% respect to the reference scenario. The LCA results confirm the benefits that can be obtained from the energy symbiosis network as a whole. In fact, in comparison with the reference scenario a reduction of about 3000 kg$CO_2$eq can be achieved (Table 33); the two impact categories are the carbon originated from fossil fuels, biogenic sources and land transformation and the carbon stored in plants and trees as they grow (carbon uptake) calculated with the Greenhouse Gas Protocol (GHG) assessment method, and the 20-year time horizon Global Warming Potential (GWP) based on the Intergovernmental Panel on Climate Change (IPCC) assessment method.

| **Impact** (kg$CO_2$eq) | **Reference scenario** | **Symbiosis scenario** | **% reduction** |
|---|---|---|---|
| Fossil $CO_2$eq | 70410 | 2977.9 | 95.62 |
| IPPC GWP 20a | 76844 | 3360.7 | 95.77 |

*Table 33. LCA results of the system for the reference and the symbiosis scenario.*

Then, the same LCA method applied to individual firms in the network, confirmed the same results. Considering, as an example, the firm B6, in the symbiosis scenario 2, it receives energy from suppliers S1, S2 and S3, and from the PV plant P1 and the wind plant W1 (Figure 19).

15 for the details of LCA modelling applied to energy symbiosis and calculations, refer to the paper S. Marinelli, M.A. Butturi, B. Rimini, R. Gamberini, S. Marinello, *Evaluating the environmental benefit of energy symbiosis networks in eco-industrial parks*, to be published in the proceedings of the 21st IFAC World Congress (Virtual), Berlin, Germany, July 12-17, 2020 (IFAC PapersOnLine).

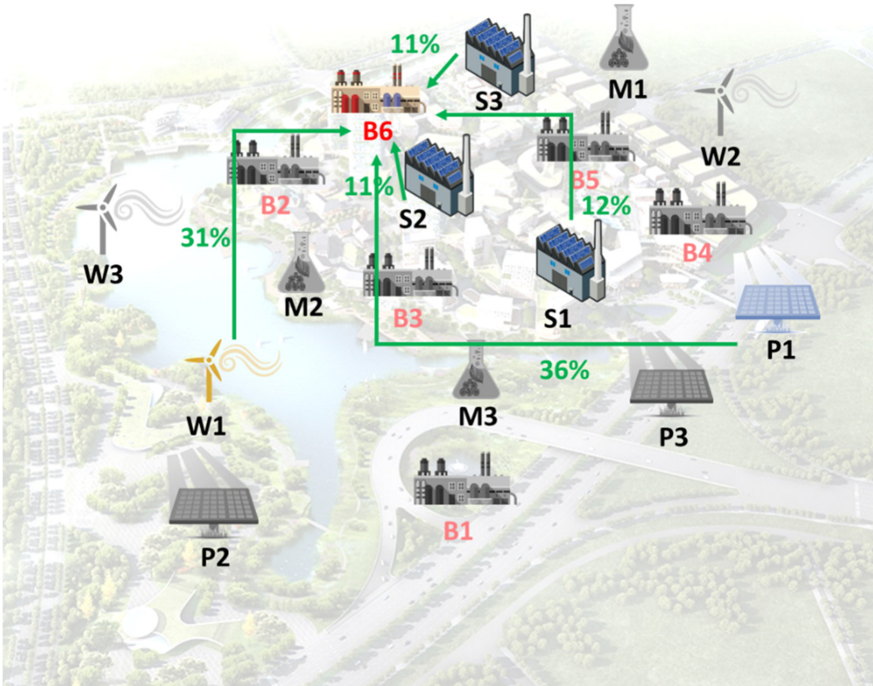


*Figure 19. Energy inputs for the buyer B6.*

The symbiotic scenario is compared with a reference scenario in which firm B6 uses only energy from the national grid, without any energy exchanges and RES contributions. Also in the individual case, the results, listed in Table 34, show a reduction of almost 96% of kg$CO_2$eq.

| **Impact** (kg$CO_2$eq) | **Reference scenario** | **Symbiosis scenario** | **% reduction** |
|---|---|---|---|
| Fossil $CO_2$eq | 13235 | 423.45 | 96.80 |
| IPPC GWP 20a | 14890 | 478.76 | 96.78 |

*Table 34. LCA results for the reference and the symbiosis scenario of the B6 firm.*

The main limitation of the presented analysis is that the data are only representative: real case studies, though it is rather difficult to collect real data, are needed to stress and validate the model.

## 2.3 A Case Study

The focus on energy flows within EIPs is also justified by the fact that the electrification of some industrial processes supported by the use of combined RES offers a recognized potential for emissions reduction where resources abundance allows to lower the cost of electricity (IEA/OECD and Cédric Philibert, 2017).

Energy intensive industries (EIIs) account for about 15% of the total greenhouse gas (GHG) emissions in the EU (Wyns, T., Khandekar, G., Robson, 2018). Aiming at the EU targets by 2050[16], several possible emissions abatement solutions for the energy intensive industry have been investigated by the literature (Bataille *et al.*, 2018; Gerres *et al.*, 2019).

In this section, the developed model is applied to investigate the potential environmental benefits achieved by means of industrial energy symbiosis (IES) initiatives integrating RES in the case of an Italian EII committed to the environment preservation. In particular, the model is applied to explore

[16] A Roadmap for Moving to a Competitive Low Carbon Economy in 2050. European Commission (2011).

the opportunities of carbon emissions reduction of an EII located in the Emilia Romagna region through the activation of electricity exchanges with neighbor firms. To demonstrate the potential environmental benefits, the $CO_2$ emissions of both a common electrification strategy and the optimized scenarios are calculated and compared with the reference scenario, using the LCA method.

### 2.3.1 The reference scenario

The considered EII approached to an energy audit (diagnosis) in 2018 to uncovers the critical issues and plan strategies for improving its energy system.

The main consumptions categories of the EII are electric energy, natural gas and diesel due to activities that can be divided into the following three functional areas: main activities, auxiliary activities, and general services. The main energy consumption is the natural gas that accounts for the 57% of the total, used in four industrial furnaces for drying operations. The remaining consumptions are equally divided into electricity (21%), used firstly for main activities and secondly for general services (as conditioning and lighting), and diesel (22%) used for auxiliary activities and general services (as internal goods movement) (Figure 20).

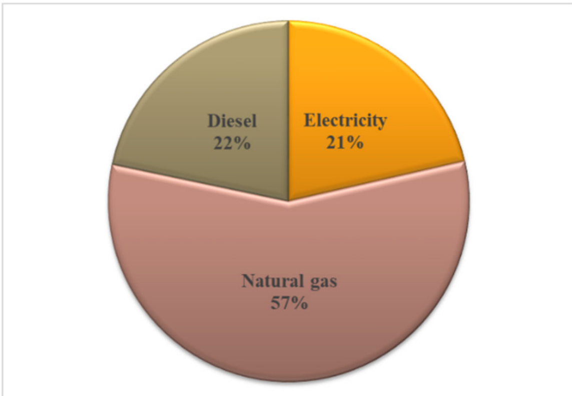


*Figure 20. : EII's annual energy consumption for energy carrier*

The study of the consumptions outlined two viable energy reduction strategies:

- reduction of lighting energy consumption by the replacement of obsolete lamps with LED units;
- optimization of auxiliary processes and plants that utilize electric energy by the installation of inverters able to regulate the energy absorption.

#### *2.3.1.1 Electrification strategy*

The electrification of existing industrial plants is one of the most preferred strategies applied to reduce carbon emissions (Bühler *et al.*, 2019). In the specific case, the utilities available to the application of this strategy were the four industrial furnaces dedicated to drying processes. The electrification of the vehicles used for internal goods movement was not suitable because the vehicle fleet consists mainly of trucks, while the thermal recovery, because of the intermittent use of the four furnaces, was not considered an advantageous strategy.
However, the environmental analysis of different electrification scenarios considering the replacement of one or more furnaces with electric ones, without changing the standard Italian electricity mix in input, showed that the carbon emissions increase up to 3%, remaining essentially unchanged.

### 2.3.2 Industrial energy symbiosis scenario

The considered company, B1-EEI, is located in the Emilia-Romagna region, in the northern Italy. In the territory, farms coexist with a rich entrepreneurial fabric made up of many small and medium-sized businesses. According to Italian law (D.Lgs.112/1998), the Emilia-Romagna region promotes the transition of industrial districts to more sustainable “eco-industrial parks”, defined as “industrial zone equipped with infrastructure and systems able to guarantee health, safety and environment protection”. Thus, the local policy supports the creation of synergies among firms, making the industrial energy symbiosis approach a viable solution.

Considering a neighbouring area within about 20 km, the maximum distance between two connected facilities allowed by the model to avoid high cost for the connection infrastructure, we find out some companies that could be involved in IES initiatives (Figure 21). Two SME companies (B2 and B3) with medium and low electricity consumption profiles (respectively 540 MWh/y and 23 MWh/y) and two companies with energy surplus (S1 and S2) are located in the same district. S1 owns a photovoltaic plant installed on the firm’s roof that can supply an average electric energy surplus of 610 MWh/y. The plant was installed when the “Conto Energia” Italian Law incentivized the renewable power production. S2 is a big farm that installed a biomass plant to process poplar wood and wood waste; it can supply an average electric surplus of 1840 MWh/y. The electrical energy surplus of both S1 and S2 is now provided to the public multi-utility.

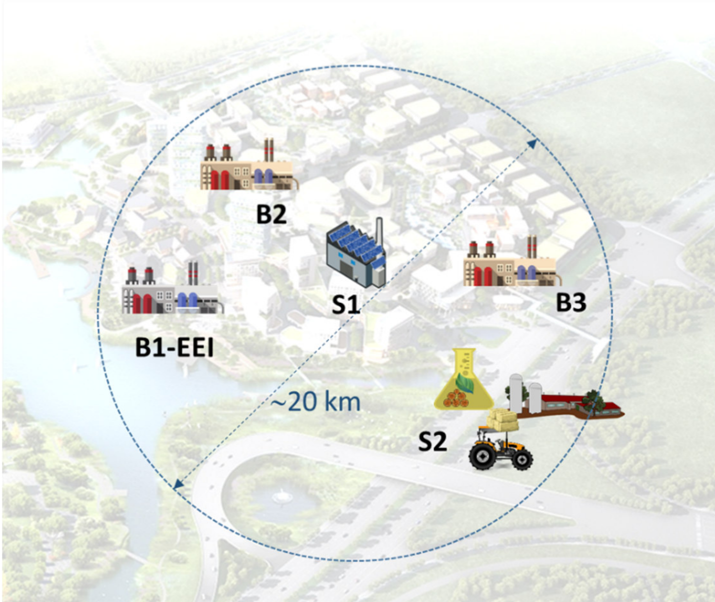


*Figure 21. Group of nearby companies, that can be modelled as an industrial park, in an energy symbiosis perspective.*

The five organisations can be viewed as an industrial district and the potential energy synergies can be evaluated. Thus, the model (3) can be applied, aiming at minimizing simultaneously both the costs and the environmental impact of the energy exchanges, considering at the same time both the buyers’ and the suppliers’ benefits. An adapted version (27), of the originally developed model (3), has been developed to fit the case study. The adapted model does not consider the distance among firms to keep costs down, as the distances are fixed (constraint (14)). Moreover, it does not consider the possible installation of RES plants, due to spatial limits.

$$\min Z'_3 = \sum_{t\in T}\left\{\sum_{j\in J}\left[FD_j^t(1-h_j^t)+VD_j^tD_j^t\left(1-\sum_{i\in I}y_{ij}^t\right)\right]+\sum_{j\in J}\sum_{i\in I.Sup}\left(FC_i^t x_{ij}^t+RC_i^t D_j^t y_{ij}^t\right)+\sum_{j\in J}\left[EC^t IP_j^t D_j^t(1-y_{ij}^t)-EC^t\sum_{i\in I.Sup}EP_i^t D_j^t y_{ij}^t\right]\right\}(1+s)^{-t}+\sum_{j\in J}\sum_{i\in I}CC_{ij}w_{ij} \quad (27)$$

Accordingly, the constraints (19), (20) and (21), considering the installation of new renewable power units, are not considered.

#### *2.3.2.1 Modelled scenarios*

In this case, the model has been coded and elaborated using the domain-specific modelling language for mathematical optimization JuMP embedded in Julia, an open source programming language developed at MIT.

Different scenarios have been built up, considering both the current electricity demand for organization B1 (scenario *as is*) and the improved electricity demand due to processes electrification. With regard to the electrification of the furnaces, the two scenarios consider the electrification of the smaller furnace (EL1), with the increase of the electric energy consumption of about 26% respect the *as is* scenario, and the electrification of the most consuming furnace (EL2), with the increase of the electric energy consumption of about 63% respect the *as is* scenario.

The model minimizes simultaneously the major costs and environmental impacts of the energy inter-firm exchanges. It provides the optimized energy flows between supplying and buying facilities per year, on the total temporal range of 20 years. Figure 22 presents a representative picture of the results, showing advantageous energy connections from a collective point of view in the three different scenarios. The average amount of the energy demand satisfied over the entire period T is shown in percentage.

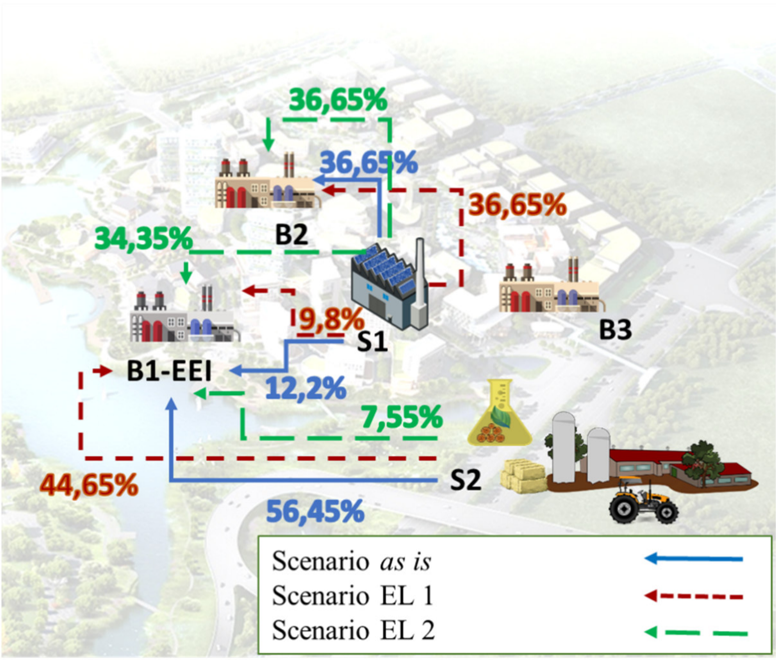


*Figure 22. Modelled advantageous energy connections.*

Overall, in the scenarios *as is* and EL 1, the biomass plant owned by S2 is the main supplier for B1, while in the scenario EL 2, the PV plant installed on the roof of S2 supplies the greater amount of electricity to B1. All the available energy surplus is provided in the three scenarios. It can be observed that buyer B3, the small industry energy consumer, is not included in the energy synergies, since the cost of connections does not result advantageous.

#### *2.3.2.2 LCA evaluation*

To analyse the environmental benefits provided in the modelled scenarios, the LCA analysis of the resulting energy connections has been performed, assessing the change in $CO_2$ emissions with respect to the reference scenario.

The largest reduction is illustrated when comparing the reference scenario with the scenario as is and EL 1. The sharing of RES energy coming from S1 and S2 can lead to a reduction of roughly 3.65E+07 kg $CO_2$ eq corresponding to a decrease of GWP equal to the 33%. When reviewing the scenario EL 2, results show a reduction of GHG emissions of about the 29% (3.21E+07 kg $CO_2$ eq) (Figure 23).

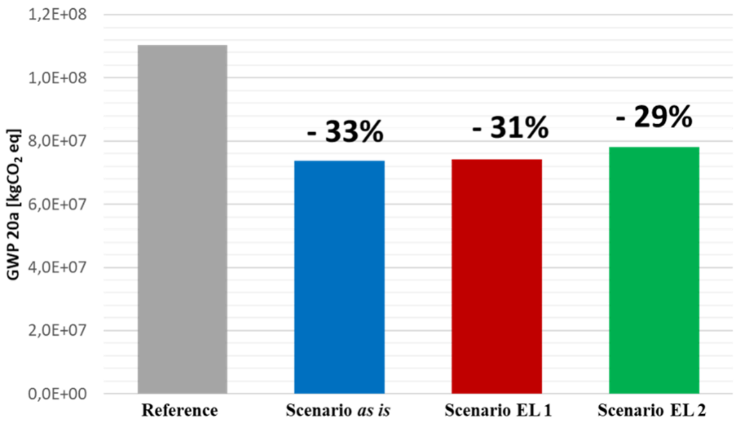


*Figure 23. Overview of the modelled scenarios LCA*

The results demonstrate that the collective energy strategy including RES can allow to achieve a higher environmental benefit than operating at individual level.

# *Chapter 4*
# Designing an urban-industrial energy symbiosis project integrating RES

The urban-industrial symbiosis concept arose from existing industrial symbiosis projects, to fully exploit the advantages of a collaborative approach in reducing the environmental impact at local level. Urban-industrial symbiosis extends the concept of industrial symbiosis to urban-industrial synergies. Taking advantage of geographic proximity, it promotes the exchanges of waste, resources and energy between urban and industrial areas, as well as the sharing of infrastructure.

The urban-industrial symbiosis can support both urban transition towards sustainability and industrial green innovation, through creating advantageous relationships in the framework of a common low-carbon strategy between industrial districts and neighbouring urban areas.

This chapter focuses on the main UIS approaches involving low-carbon energy links between industries and cities, aiming at investigating the potential of creating RES synergies at urban-industrial level. A project for the implementation of a local energy-based urban industrial symbiosis is designed.

This chapter is partially adapted from the paper:

- *Urban–industrial symbiosis to support sustainable energy transition,* published in 2020 in the International Journal of Energy Production and Management 5 (4), 355-366.

# 1 URBAN-INDUSTRIAL SYMBIOSIS

An integrated approach to urban sustainable development should involve the neighboring territory and business areas to guarantee optimized planning strategy and long term perspective (Bian *et al.*, 2020). This integrated approach can be realized through the urban-industrial symbiosis (UIS).

The concept of urban-industrial symbiosis has emerged firstly in relation to the Japanese Eco-Town Program (Van Berkel, Fujita, Hashimoto and Geng, 2009). 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.

The urban-industrial symbiosis can be considered as an extension of the industrial symbiosis, that aims at creating advantageous synergies between firms. According to the UNIDO, clustering of industries and the creation of eco-industrial parks promote the development of urban-industrial synergies and allow to reduce the cost of joint infrastructure (UNIDO, 2019). In fact, 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 (Karner, Theissing and Kienberger, 2016). (Simeoni, Nardin and Ciotti, 2018) 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.

As the IS can bring benefits to the local communities allowing to save local resources and by reducing waste to be managed by local infrastructure (Chertow *et al.*, 2019), the UIS builds up relationships between cities and local industrial sites that can harmonize the coexistence of living and production areas (Dong *et al.*, 2017), improving the environmental, social and economic sustainability of the whole system.

The contribution of UIS to the circular economy promotion as well as to the reduction of urban and industry environmental impact is widely recognised (Fujii *et al.*, 2016; Dong *et al.*, 2017; Sun *et al.*, 2020) and the environmental benefits quantified (Ohnishi *et al.*, 2017; Lu *et al.*, 2020).

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. The most studied UIS experiences consider Asian countries' national programs. Along with the Japanese Eco-Town Program, 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. Successful low carbon strategies have been implemented in China through advantageous relationships between industrial parks and urban communities, where material symbiosis (mainly urban waste recycling systems) is more common than energy symbiosis, probably due to the physical characteristics of energy that is more unstable to transport and requires costly transportation infrastructure (H. Dong *et al.*, 2014).

The basic concept underpinning the UIS approach is that urban waste can be delivered to nearby industrial clusters for incineration or recycling, while industries can provide back available extra electrical or thermal energy. In fact, some industrial sites are equipped with waste/sludge treatment facilities and can benefit from using urban waste as fuel, improving plant saturation. From the urban point of view, this allows reducing waste landfill.

Waste flows from cities to industrial sites can be manifold. Some representative solutions are listed below:

- Municipal solid waste can be incinerated for heat recovering and power generation (Marchi, Zanoni and Zavanella, 2017; Sun *et al.*, 2020) or production of intermediate fuel (Van Berkel, Fujita, Hashimoto and Geng, 2009); it can be delivered for fuelling industrial furnaces, mainly in energy intensive industries, such as iron/steel, cement (Sun *et al.*, 2020) and paper industry (L. Dong *et al.*, 2014); mixed plastics are used for ammonia production (Van Berkel, Fujita, Hashimoto and Fujii, 2009) and as reductant in iron industry, and fly ash can be used by cement industry (Dong *et al.*, 2013).
- Separately collected materials can be recycled, if recycling companies are established within the industrial district: plastics (Van Berkel, Fujita, Hashimoto and Fujii, 2009), steel (Dong *et al.*, 2013), glass and electronic waste (Van Berkel, Fujita, Hashimoto and Fujii, 2009); or re-used as alternative raw materials like plastics in cement or scrap tyres (L. Dong *et al.*, 2014; Fang *et al.*, 2017).
- Organic waste can be used for energy production (e.g., by anaerobic digestion, pyrolysis, or gasification) (Albino, Fraccascia and Savino, 2015), sometimes managed by a public multi-utility (Marchi, Zanoni and Zavanella, 2017).
- Urban waste water can be collected and treated to be re-used in industrial processes (i.e. in iron/steel industry (Dong *et al.*, 2013)).
- Sewage sludge can be used for energy production (Sokka, Pakarinen and Melanen, 2011).

On the other hand, the waste heat resulting from industrial processes can be supplied to the urban areas.

(Kim, Dong, *et al.*, 2018) evaluated the environmental and economic benefits of re-using industrial waste heat at both industrial and urban levels analysing a urban-industrial symbiosis scenario linking the Onsan and Ulsan-Mipo national industrial parks to Ulsan city (South Korea). Two heat recovery systems were 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. The economic advantage of this symbiosis was demonstrated considering that the cost of the initial investment was shared at EIP and public levels.

Figure 24 presents a graphical representation of the overviewed urban-industrial synergies.

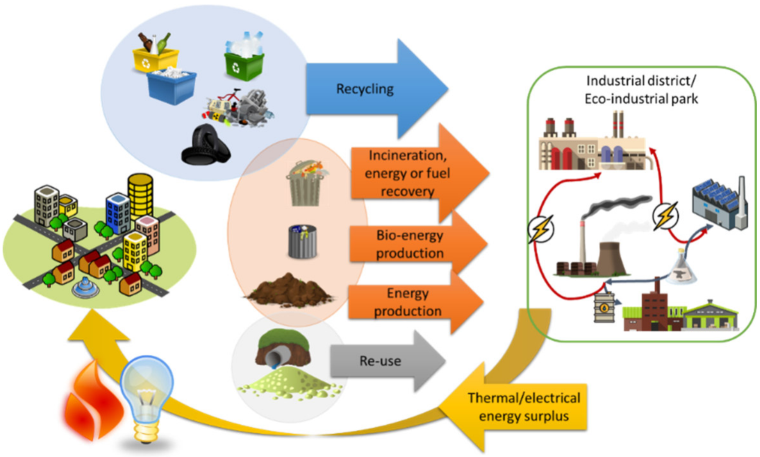


*Figure 24. Potential and existing resources exchanges within UIS framework.*

From the previous literature overview, some materials flow from the city to the industrial district can be categorized as energy based, since exchanged materials are converted in energy (orange arrows in the picture). Similarly, heat or electricity surplus can flow form the industrial district to the urban area (yellow arrow in the picture).

## 1.1 ENERGY-BASED UIS

The energy-based IS projects involving urban areas available in literature concern mainly the energy production from urban wastes, and the heat recovering from industrial processes or co-generation plants for district heating (Fraccascia, 2018).

District heating (DH) 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 (Lund *et al.*, 2014).

Through a DH model, high- and low-grade heat can serve both residential and commercial buildings (department stores, office buildings, hospitals). This solution is considered an effective way to reduce the environmental impact at local urban level and, considering the need for heat pipelines, the geographic proximity between energy consumers and industrial suppliers is a key factor (Fang *et al.*, 2013; Togawa *et al.*, 2014). Since the infrastructure investment cost can have a long pay-back time, the implementation strategy should be based on a public-private business model and take into account stakeholders' participation (Kim, Dong, *et al.*, 2018). Moreover, since the installation and operation phases of heat management plants are not the main businesses of manufacturing firms, a service company should at least partially finance the project and handle the operation of the district heating grid (Karner, Theissing and Kienberger, 2017). Low grade industrial heat as well as industrial wastewater, mainly produced by pulp and paper and food industry in a temperature range 35°-90°C, can be used for heating/cooling through heat pumps. There is a long history of research and applications into DH 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.

Electricity recovery or exchanges are the less common practices, probably due to the high cost or low maturity level of the storage technologies and the still little diffusion of tools for the demand response management (Holgado *et al.*, 2016). Storage facilities should also take into account the time shifts between the energy demand in cities and the energy supplying by industry (Karner, Theissing and Kienberger, 2016). In the Table 35 some common energy-based synergies selected from the literature are presented.

| UIS involving energy exchanges | Energy to city | Energy to EIP | Source |
|---|---|---|---|
| Coal plant/combined heat and power (CHP) plant | X | | (Lu *et al.*, 2020) |
| Incineration plant fuelled by MSW | | X | (Fang *et al.*, 2017; Marchi, Zanoni and Zavanella, 2017; Kim, Dong, *et al.*, 2018; Lu *et al.*, 2020) |
| Biomass plant fuelled by urban organic waste | | X | (Marchi, Zanoni and Zavanella, 2017; Kim, Dong, *et al.*, 2018; Lu *et al.*, 2020) |
| Co-generation plant and power generation | X | | (Dong *et al.*, 2016) |
| Industrial waste heat from industrial processes (DH model) | X | | (Fang *et al.*, 2013, 2017; Togawa *et al.*, 2014; Karner, Theissing and Kienberger, 2016; Afshari, Jaber and Searcy, 2018; Kim, Dong, *et al.*, 2018) |
| On-roof photovoltaic and solar thermal plants | X | X | (Karner, Theissing and Kienberger, 2016) |
| Wind turbine installation in EIPs | X | X | (Maes *et al.*, 2011) |
| Low grade industrial waste heat (heat pump – Rankine cycle) | X | | (Karner, Theissing and Kienberger, 2016) |
| Wastewater (heat pump) | X | | (Karner, Theissing and Kienberger, 2016) |

*Table 35. Energy based synergies at urban-industrial level.*

Interestingly, in their overview of the possible synergies between industries and nearby towns summarized in (Karner, Theissing and Kienberger, 2016), introduce the exploitation of industrial empty roof space, in which photovoltaic plants for renewable power generation can be installed Table 36.

| 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 36. Possible energy carriers and usage in an urban-industrial context.*

(Afshari, Jaber and Searcy, 2018) 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.

## 1.2 RES IN URBAN-INDUSTRIAL CONTEXT

Since urban areas play an important role in energy consumption and carbon emissions, the neighbour EIPs can provide clean energy to local communities, thus improving the social role of industry. In the process of transformation of the industrial parks of Flanders (Belgium) into eco-industrial parks, the local authorities noticed that, according to local communities expectations, when renewable energy plants, such as for wind turbines, raise issues concerning spatial impact, the industrial parks can be the most acceptable places to install them (Maes *et al.*, 2011). Moreover, as pointed out in the above section, often companies have large empty roof space where photovoltaics (PV) or solar thermal collectors could be installed to provide renewable energy to residential and commercial areas; different business models should be considered involving the company itself (that can both finance and operate the project or rent the roof), an external service company for financing and operating the project, and the citizens that could participate in the project financing (Table 37).

| 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 through DH-grid | The company itself | The company itself | | Rather unlikely since the capital commitment and the amortization time are too long |
| | A service company | A service company | | |

*Table 37. Business models for industrial energy project implementation, as in (Karner, Theissing and Kienberger, 2017).*

The different business models for financing and operating plants that supply industrial energy have been extrapolated analysing the economic viability of using industrial energy in urban context, and particularly in four urban regions in Austria. The studied model showed that up to 35% of the total urban energy demand, and 6–46% of the electricity demand, could be supplied by industrial energy thus lowering $CO_2$ emissions. 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.

The available business models to generate renewable power within the Italian grid, according to GSE (Gestore dei Servizi Energetici – the authority for the Italian energy system management) are shown in the Figure 25.

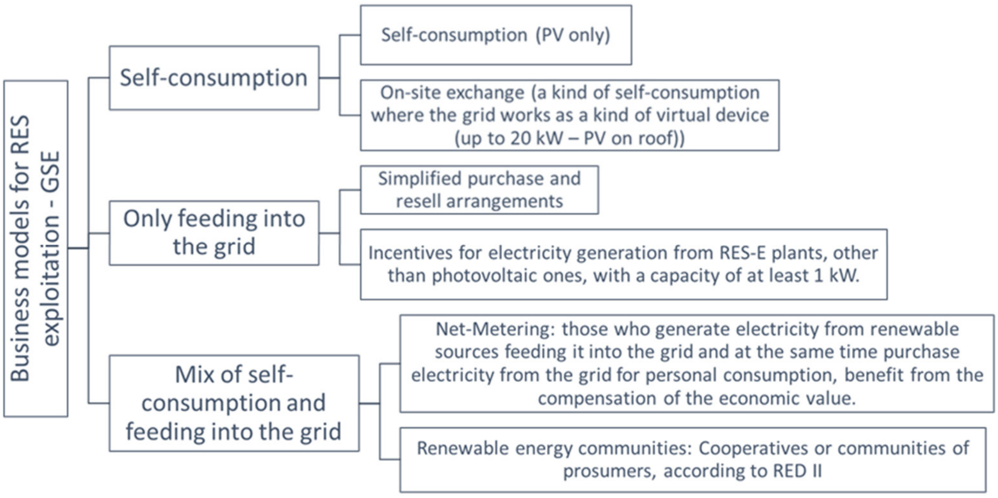


*Figure 25. Possible business models for RES exploitation according to the Italian law (source: GSE[17]).*

A number of business models are available, allowing mechanisms for self-consumption of the generated power, exchanges with the main grid that imply incentives and the possibility of collective projects, taking the legal form of cooperatives or renewable energy communities that own the power plant, and can use and sell the electricity surplus.

Many community ownership initiatives are ongoing in Europe, with different legal structures (Caramizaru and Uihlein, 2019), Table 38:

| **Legal structure** | **Description** |
|---|---|
| Energy cooperatives | This type of ownership, mainly citizen-led initiatives, primarily benefits its members. It is popular in countries where renewables and community energy are relatively advanced. |
| Limited partnership | The model is suitable for larger projects with high investment volume, with a limited liability company as a general partner. Voting rights are proportional to the capital invested, instead of the traditional one member-one vote. |
| Community trusts and foundations | Their objective is to generate social value and local development rather than benefits for individual members. Profits are used for the community as a whole, even when citizens do not have the means to invest in projects (for-the-public-good companies). |
| Housing associations | Non-profit associations that can offer benefits to tenants in social housing, although they may not be directly involved in decision-making. These forms are ideal for addressing energy poverty. |
| Non-profit customer- owned enterprises | Used by communities that deal with the management of independent grid networks (e.g. district heating networks). |
| Public-private partnerships | Local authorities can decide to enter into agreements with citizen groups and businesses in order to ensure energy provision and other benefits for a community. |
| Public utility company | Public utility companies are run by municipalities, who invest in and manage the utility on behalf of taxpayers and citizens. |

*Table 38. Rewieved legal structures for energy communities (from (Caramizaru and Uihlein, 2019)).*

[17] https://www.gse.it/servizi-per-te

### 1.2.1 Load profiles complementarity

To maximise the technical performance and the beneficial impact that the renewable technologies can have on the energy system, they should be installed close to electric loads, taking into and their temporal power profiles match the local load's time curves (Henninger and Jaeger, 2018). Considering the energy-based UIS approach, the specific energy consumption patterns of residential, commercial and industrial sectors are sometimes complementary: as an example, respect to solar power production peaks, commercial and residential electricity demand is complementary. The next Figure 26 shows typical residential and commercial loads over two days (one weekend and one weekday).

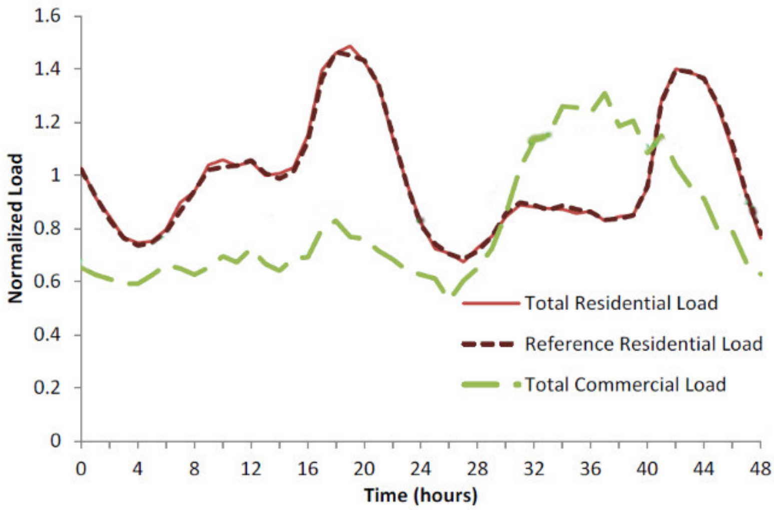


*Figure 26. Typical residential (brown) and commercial (green) loads over two days (one weekend, one workday)* (Hoke *et al.*, 2012).

Considering a workday (hours 24 to 48 in the graph) the typical residential electric load shows a small plateau in the morning hours and a peak in the evening (about 8 PM); on the other hand, the commercial load shows a peak during the midday hours, when the commercial activities are operating. Comparing the PV generation daily profile (without considering the seasonal variations) with the two different load profiles (Figure 27) it can be seen that it matches better the commercial load profile.

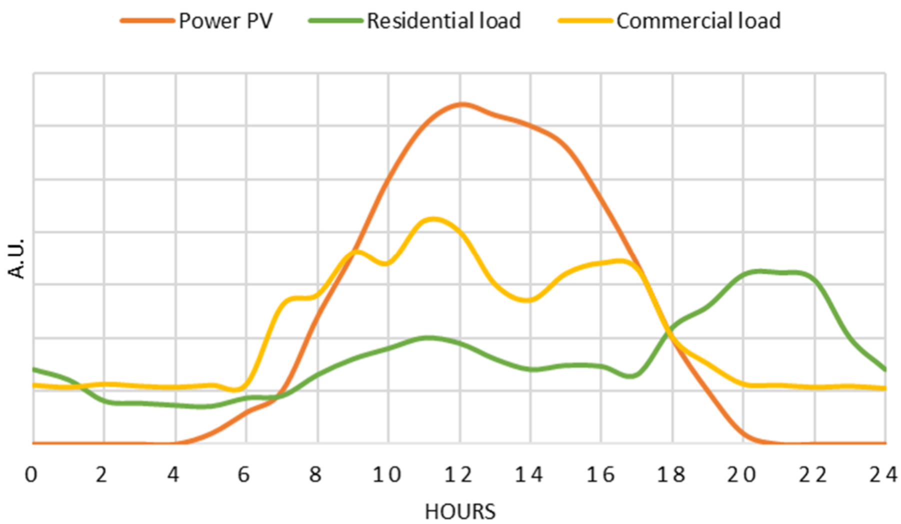


*Figure 27. Comparison between PV power generation daily profile (orange) and residential (green) and commercial (yellow) load (the graph is only representative of typical fix c-Si PV system and residential and load profiles as collected in literature).*

As far as concern industrial load daily and seasonal profiles, they depend on the considered industry. It is difficult to collect data on load profiles (for example on hourly basis), and, since they are valuable data both for industry, that own them, and for utilities/energy providers, there are few publications reporting them. Some representative profiles representing the total electricity consumption per sector, are compared in Figure 28, where it can be seen that industry load peaks, globally, are during the day hours.

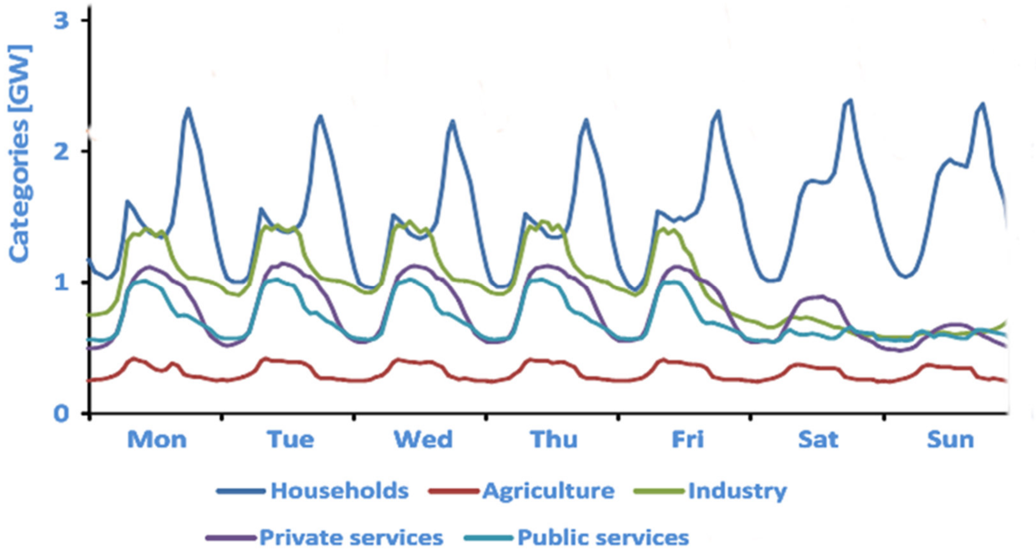


*Figure 28. Hourly consumption by categories of customers in 2010 (from (Andersen, Larsen and Boomsma, 2013)).*

From the previous analysis on the electric load profiles, it derives that urban and industrial energy demand can be satisfied by combining various sources of energy: in analogy with the smart grid concept, a smart energy system approach is suggested by Lund et al. (Lund *et al.*, 2017) to combine electricity, heat and gas grids with storage technologies to allow sustainability oriented synergies among industrial, commercial and residential sectors. A regional multi-energy "prosumers" (both energy producers and consumers) scheme, based on energy hubs combining distributed energy supply, RES and CHP, is modelled to serve residential, commercial and industrial districts in (Yang *et al.*, 2016). The smart technologies allow the creation of smart infrastructures and energy management platforms between smart cities and industrial parks promoting urban industrial symbiosis integrating RES (Y. Wang *et al.*, 2019). Thus, the symbiosis strategy act as a systemic innovation approach, allowing the realisation of multi-energy systems with a high renewable energy share and the use of innovative technologies (Fujii *et al.*, 2016). Within UIS context, eco-efficiency and eco-innovation are two main advantages of industrial partners, while local communities benefit from environmental restoration and improved well-being (Van Berkel, Fujita, Hashimoto and Geng, 2009).

# 2 SUSTAINABLE CITIES

Urban areas play an important role in energy consumption and carbon emissions. Since cities sustainability strongly depends on their interconnections with the surrounding ecosystem (European Commission, 2018), they can be viewed as "superorganisms" with metabolic processes that must be controlled.

## 2.1 URBAN METABOLISM

Starting from the consideration that the urban areas can be seen as organisms exchanging materials and energy with the surrounding environment, the *urban metabolism* concept, analogous to the Industrial Ecology concept, was proposed by scholars in the late sixties of the last century. In this context, the urban area or city refer to the administrative boundary, including both the built-up area and the surrounding rural areas.

Analysing the input-output flows of urban systems allows to quantify the resources needed to sustain the lives, work, and recreation of urban residents and evaluate the associated environmental impacts, providing an effective way to trace the social, economic and natural processes occurring within cities where the transformation of raw materials produces waste emission. Once again, according to the biological metaphor the produced wastes can be turned into resources for further transformation and re-use. The proximity with eco-industrial parks can improve the circularity of resources flows reducing pollution and environmental burdens (Zhang, Yang and Yu, 2015).

Urban metabolism (UM) methods can be classified (Lucertini and Musco, 2020) as accounting approaches aiming at quantifying the achievable reduction of materials or energy use (material and energy flow analysis, exergy and emergy analysis, input-output analysis), and indicator approaches aiming at synthesizing information about consumption and impact (ecological footprint method, life-cycle analysis). Other simulations methods, as system dynamics, study the behavior of the system and the relationships between its components.

The UM approach is theoretically interesting, but it is also essential in supporting the development of sustainable public policies and strategic planning.

One of the goals of the *Strategy for urban and ecological-environmental quality and assessment of environmental and territorial sustainability of the general urban plan* of the Emilia Romagna region is the improvement of UM and the promotion of the circular economy; the strategy establishes that the study of the urban metabolism aims at creating or strengthening virtuous circuits in the use of resources and in the growth of well-being (in a circular economy view). The knowledge and management of the UM allow to optimize the flows of materials and energy, to plan the replacement of non-renewable resources with renewable ones, to aim at zeroing waste closing production and consumption cycles. Moreover, the strategy suggests that the metabolic approach can be calibrated to consider only some strategic flows, such as water, soil or energy. It can also be effectively applied at the city level, where it is possible to identify the set of flows of energy and materials entering and exiting the perimeter; once the flows are identified, the technological and behavioral innovation scenarios to close production and consumption cycles (decentralized energy, renewable sources, multiple use of water, sustainable mobility, etc.) can be built-up with the aim of reducing the economic and environmental costs of managing local activities and services, as well as the pressures on the environmental components of others parts of the city.

### 2.1.1 Energy related urban metabolism indicators

The application of the urban metabolism methods to urban planning has the aim of integrating the sustainability perspective within the urban development practices (Song *et al.*, 2018), then, the UM indicators can support the design of urban-industrial symbiosis projects. Considering the energy flows, the main energy related indicators used in urban metabolism assessment are listed in Table 39, together with the corresponding accounting method.

| *Energy related indicator* | *Accounting method* |
|---|---|
| Electricity | MFA, ESA |
| Embedded energy ratio | MFA |
| Energy balance | MFA, ESA |
| Energy consumption by cooling/heating | MFA, ESA |
| Energy consumption by transport | MFA |
| Incoming solar radiation | MFA, ESA |
| Percentage of energy from renewable sources | MFA |
| Solid, liquid and gaseous fossil fuels | MFA, ESA |
| Percentage of use of public transport | MFA |

*Table 39. Energy related indicators used in the scientific literature to analyse urban metabolism (adapted from the review of (Song et al., 2018)); MFA=material flow analysis, ESA=emergy synthesis analysis.*

These indicators can support the design of energy based UIS, providing the state-of-the-art and the possible pathways to improving circularity and the local energy system sustainability.

## 2.2 RES IN URBAN CONTEXT

Energy solutions integrating renewable energy sources (RES) at buildings, district or urban level are considered as effective way to support the urban transition towards energy sustainability (Manfren, Caputo and Costa, 2011; Zhang *et al.*, 2018). The European Energy Performance of Buildings Directive (European Parliament and Council, 2010) introduced the concept of nearly zero-energy building, with the aim of pushing for maximizing energy efficiency and increasing the share of renewable energy at building level. This approach brought along the concepts of nearly zero-energy district (NZED) and residential net zero energy system that apply to intermediate or urban scale (Amaral *et al.*, 2018; Lombardi *et al.*, 2018). These city-level approaches consider multi-energy systems to satisfy residential/commercial and public infrastructure electricity demand, as well as mobility and heating/cooling energy demand. The involved energetic systems include renewable energy technologies, and storage systems such as electric vehicles to manage the volatility of some RES.

Cities have a great potential for the adoption of RES since they can be integrated in buildings avoiding land use; moreover thanks to the local power production via distributed generation and energy hubs, the grid transmission losses can be reduced (Allegrini *et al.*, 2015). The renewable technologies that can be considered for their adaptability to urban context are solar (for the availability of roofs and surfaces on buildings), bioenergy to produce heat and power, wind (micro-turbine for micro-generation applications), and heat pumps. These technologies should be associated with seasonal storage (for example ground- or water-based thermal storage).

Rotterdam local authorities included the adoption of the UIS approach within the energy plan supporting city's climate strategy, recognizing three main steps to be fulfilled: to reduce energy consumption via architecture, to reuse waste energy flows, to use renewable energy (Lenhart, Van Vliet and Mol, 2015). The integration of RES is planned at building, neighborhood, district and central (city) scale, within an integrated framework. A micro-grid model, including solar energy, tri-generation and storage systems, applied to the city of New York showed that, in order to achieve the set target of 26% carbon reduction, industrial waste heat and substantial photovoltaic electricity should be employed (Chan, Cameron and Yoon, 2017).

# 3 URBAN-INDUSTRIAL SYMBIOSIS INTEGRATING RES – A FRAMEWORK

## 3.1 UIS INTEGRATING RES ARCHITECTURE

As discussed before, renewable energy technologies can be locally adopted at buildings level (residential, industrial - warehouse or office - and commercial), at district or at central level (joint projects between the industrial district and the city). Collective power production and distributed generation resources can allow the integration of a high share of RES. Also in the case of UIS, a smart multi-energy grid configuration, controlled according to the energy hub model, can manage the energy exchanges between the city and the industrial park (Figure 29). The energy hub works essentially as an interface between primary energy sources and end-users, while communication platforms allow an effective exchange of information among actors. 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 (Y. Wang *et al.*, 2019).

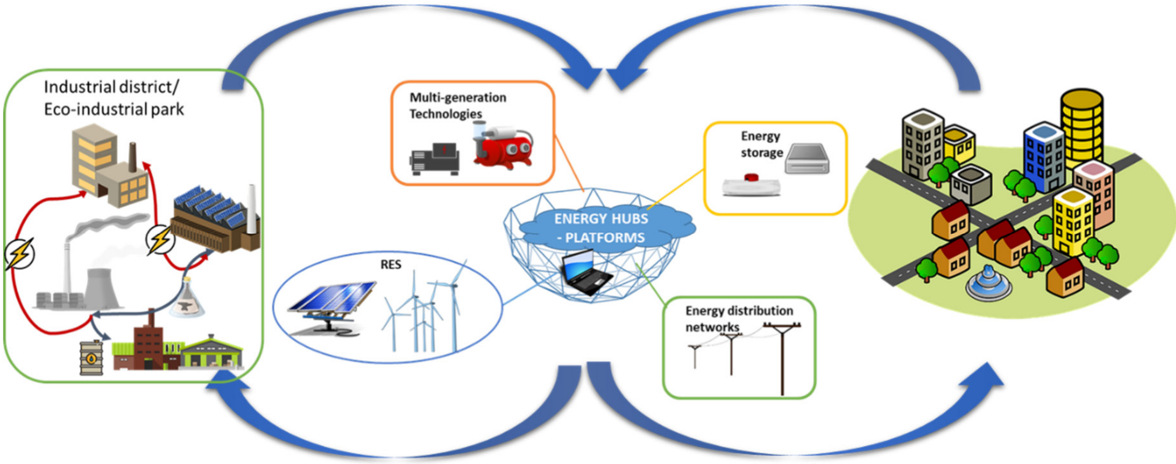


*Figure 29. The smart multi-energy grid configuration, supported by information exchanges platforms, manages the energy hubs serving the UIS.*

The main renewable energy conversion technologies fitting UIS projects combine the RES suitable for industrial and residential applications: waste/biomass treatment plants, wind turbines, solar panels (thermal collectors and photovoltaic units), ground-source heat pumps; also the carbon capture and storage technology, to transform carbon dioxide emitted in atmosphere into fuel and other products, is suggested for application in UIS (Neves *et al.*, 2020b).

## 3.2 CRITICAL ISSUES

Some critical issues must be taken into account when modelling UIS integrating RES. They can be technical, economic, regulatory or organizational (Fraccascia, 2018; Kurdve, Jönsson and Granzell, 2018).

*Multiple stakeholders' involvement*: the strong cooperation and knowledge sharing among the involved stakeholders, who must s*hare a strong commitment to the sustainability development goals,* is the prerequisite for a UIS project.

*Resource availability*: the resource (biomass, solar radiation or wind) must be locally available to guarantee the *economic feasibility*.

*Flexibility*: A number of flexibility options, such as energy storage systems or the inclusion of electric vehicles, must be considered to increase the whole system reliability by decoupling temporally demand and supply (Baumann *et al.*, 2019).

*Space*: The land or buildings space availability must be investigated and the general agreement for the installation sites reached; the geographic proximity must be defined.

### 3.3 The multi-stakeholders view

As previously observed, a main characteristic of UIS projects is the high complexity due to the involvement of multiple stakeholders. Industrial partners, energy service providers, citizens and local authorities are the main actors involved in the project, including also academia with the role of enhancing innovation, promoting knowledge sharing and providing information about the project potential results, and supporting the alignment of goals (Kurdve, Jönsson and Granzell, 2018).

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 eco-park (Le Tellier *et al.*, 2019), highlighting the need for a collective awareness and effort in implementing sustainable strategies.

Local authorities play a key role in the realization of UIS projects integrating RES. This is strongly pursued by the local authorities through policy actions and subsidies, supporting directly the UIS project, RES installation or innovation measures and infrastructure (Yu, Han and Cui, 2015; Fraccascia, 2019). Moreover, they can facilitate the other stakeholders' awareness on symbiosis and clean energy advantages and their engagement in the project (Tao *et al.*, 2019).

Stakeholders with different objectives must be kept together by the common low carbon strategy. The main goal of the industrial partners is profit, and energy related innovation may not represent a primary concern. On the other hand, communities ask for reducing industrial environmental impact and, at the same time, for creating jobs and reducing energy bill. Local authorities, starting from the low carbon strategy, aim at maximizing the economic, environmental, and social advantages of the UIS project. A collective point of view must be synthetized (Figure 30) and analysed.


*Figure 30. The multi-stakeholder view.*

On these basis, a multi-objective approach can allow to facilitate the trade-off between conflicting objectives, such as minimisation of both costs and carbon emissions (Timmerman, Vandevelde and Van Eetvelde, 2014).

### 3.4 Sustainability aspects

As for the industrial energy symbiosis projects, for energy based UIS the most investigated sustainability aspects are related to techno-economic feasibility and economic convenience, and to the environmental impacts, while only few authors consider also social benefits.

The economic sustainability must allow the energy stakeholders, industries, and local communities to achieve economic growth. The economic feasibility is influenced by the fossil fuel prices and the allowed conventional fuel saving, the cost effectiveness of installing renewable technologies, namely by the renewable technology cost (considering also the operating phase) and the renewable source availability. The intermittence of some RES has also to be taken into account, since it may require additional investments considering energy storage devices (Liew *et al.*, 2017b). The cost of network connections must also be considered.

From the environmental point of view, the reduction of carbon emissions is the main criteria considered as it is the project trigger. The emissions of renewable technologies in the operating phase is generally considered null, however, even if renewable energy sources are conventionally claimed as clean energy, a life cycle based evaluation can provide a clearer understanding of the environmental impact reduction (Liew *et al.*, 2017b).

The social sustainability pertains social well-being and progress of the involved community. The social expected benefits of the energy based UIS projects are jobs creation, energy bills reduction and improved health due to the reduction of carbon dioxide emissions (Sierra, Yepes and Pellicer, 2018; Reuter *et al.*, 2020). Afshari et al. (Afshari *et al.*, 2020) introduce in their multi-objective optimization model a "social value preference" index, a qualitative parameter representing the values of suppliers perceived by customers according to a set of environmental and social criteria.

### 3.5 Social Impacts in Energy Clustering Projects

The social impacts can be seen as the consequences to human populations of actions, such as the implementation of new technologies, that modify the way in which the people live and/or affects their complex of cultural values and beliefs. Originally, social indicators were developed to assess societies' economic growth (e.g. the GNP), while they are now adopted and widely analyzed in the scientific literature to assess the technological impacts as well as the political strategies effects on the people's quality of life.

As the importance of social dimensions in the sustainability assessment of energy projects is widely recognized (Fonseca *et al.*, 2021), though sometimes neglected in favor of the economic and environmental criteria, this section analyses the social impacts in energy clustering projects with the aim of build up a set of suitable social criteria. This analysis must integrate the different aspects involved in the energy symbiosis approach, namely the social impacts related to energy projects and to EIPs, the specificity of the distributed energy systems configuration integrating RES and the opportunities disclosed by the energy-based urban-industrial symbiosis approach.

#### 3.5.1 Social indicators for the sustainability assessment of energy systems

Although the sustainability assessment of energy projects typically includes some social indicators (chapter 2, section 4), the social aspects are often under-investigated, mainly because the social effects are difficult to quantify. Nevertheless, some comprehensive reviews provide a wide set of social indicators linking social impacts to energy system-related aspects.

With the goal of assessing the impacts of utility-scale energy systems for the European Union, within the framework of the EU funded NEEDS project a set of 26 indicators was selected among the 1320 reviewed. They were classified according to four overarching criteria, namely *continuity of energy service over time*, *political stability and legitimacy*, *social components of risk* and *quality of life*. The set was validated by a group of energy experts (Gallego Carrera and Mack, 2010). Here the focus is clearly on large-scale plants, including nuclear ones, strongly impacting the installation sites. The three social indicators reviewed by (Wang *et al.*, 2009) as typical for energy supply systems, namely *social acceptability*, *job creation* and *social benefits*, are included in the previous "quality of life" category.

### 3.5.2 Social impacts of EIPs and Industrial Symbiosis

The social impact of synergies within EIPs can be considered on two levels: the internal level, involving the participating firms and the workers, and the external level, affecting the local communities. The benefits of symbiosis projects on knowledge, training and skills of the workers, improving business performance and competitiveness, as well as the importance of employee health and well-being are widely recognised (Veleva *et al.*, 2015).

A set of social indicators related to EIPs, as collected from some reviews (Valenzuela-Venegas, Salgado and Díaz-Alvarado, 2016; Pilouk and Koottatep, 2017; Zhao, Zhao and Guo, 2017) is presented in Table 40. The indicators explicitly related to materials exchanges are not considered; indicators measuring the same social impact with slightly different nuance (e.g. *job creation* and *employment contribution*) have been grouped in one representative index.

Some of the listed social indicators are difficult to quantify (e.g. *Extent of public awareness degree with eco-industrial development*), and many of them are both social and economic.

The social aspects of an industrial symbiosis project in Sweden have been investigated by (Martin and Harris, 2018). The authors selected six indicators, focusing on the main features of the project:

1. Job retention and creation from synergy project implementation and operation.
2. Improvement and strengthening of the local skills basis.
3. Impact on R&D and local innovation.
4. Regional identity/ pride /sense of value.
5. Community engagement effectiveness
6. Community engagement efforts can benefit from the platforms and processes established for the realization of regional resource synergies

As can be seen the main social aspects are related to community engagement and development.

| Category | Social Indicator | Description |
|---|---|---|
| Impact at EIP level | Education and training | It measures the amount of employees trained per annum |
| | Expenditure on health and safety | It expresses the total expenditure on health and safety over the total number of employees, to give an investment in health and safety per employee |
| | Rate of occupational illnesses and accidents | |
| | Job creation | It measures new job created per annum by partnership |
| | Work satisfaction | It represents the number of sick days or number of people "happy" with their job per employee |
| | Quality of life of the employees | |
| | Employment increase promoting degree | |
| | Income distribution | It shows an average distribution of wealth and could be expressed in term of income of the top 10% of employees per income of the bottom 10% |
| | Ethical investments | It represents assets invested in business activities that are considered to be ethical |
| | Welfare services supporting the quality of life of employee families | |
| Impact at local community level | Conformity level of the industries to requirements, city plans | |
| | Increased community income | |
| | Extent of public satisfaction with local environmental quality | It measures the degree satisfaction of the population with local environmental quality |
| | Level of happiness of the surrounding communities | Reduction in the number of people complaints |
| | Extent of public awareness degree with eco-industrial development | It measures the public awareness of the population about eco-industrial development |
| | Proportion of consumers using environmental-friendly goods | |
| | Health risks | It measures the quantities of air pollutants, water pollutants, and waste discharged by manufactories into the surrounding area |
| | Rate of severe accidents affecting the communities | |
| | Quality of life | It measures the number of manufactories and traffic generated by them |
| | Involvement in community projects/ stakeholder inclusion | It shows the level of partnership with the community in which it operates |
| | Satisfaction of social needs | It can be expressed as both quantitative and qualitative indicators. It is measured in terms of financial contributions of businesses to satisfying social needs. |
| | Efficient implementation of community development funds | |

*Table 40. Set of social indicators for the EIPs.*

(Lütje and Wohlgemuth, 2020) develop a system of quantitative indicators, including social indicators, to assess the performance of IS in industrial parks. The authors distinguished input-related (addressing financial, human, and environmental resource properties) and output-related (addressing economic, social, and environmental impact categories) indicators (Table 41).

| | **Indicator** | **Unit** |
|---|---|---|
| Input related | number of jobs created | # |
| | number of joint organized social/charity events within the IS system | # |
| | investments in joint/cross-company organized social activities | €/$ |
| | number of utility-sharing and joint infrastructure projects | # |
| | investments in utility-sharing and joint infrastructure (kindergarten, mensa, canteen, cafeteria, mobility) | €/$ |
| Output related - through shared IS utilities and human resources | improved environmental, health, and safety (EHS) aspects (e.g., number of trainings, audits, workshops, activities) | # |
| | improved working conditions (e.g., number of joint bargaining activities, number of joint organizations for kindergarten, canteen, cafeteria, mobility) | # |

*Table 41. IS social indicators system as in (Lütje and Wohlgemuth, 2020).*

In this criteria system the impacts of joint infrastructure and utility sharing projects are explicitly evaluated.

Considering an industrial energy symbiosis project, (Afshari *et al.*, 2020) propose a set of indicators Figure 31 that are the aggregated to define a social value index.

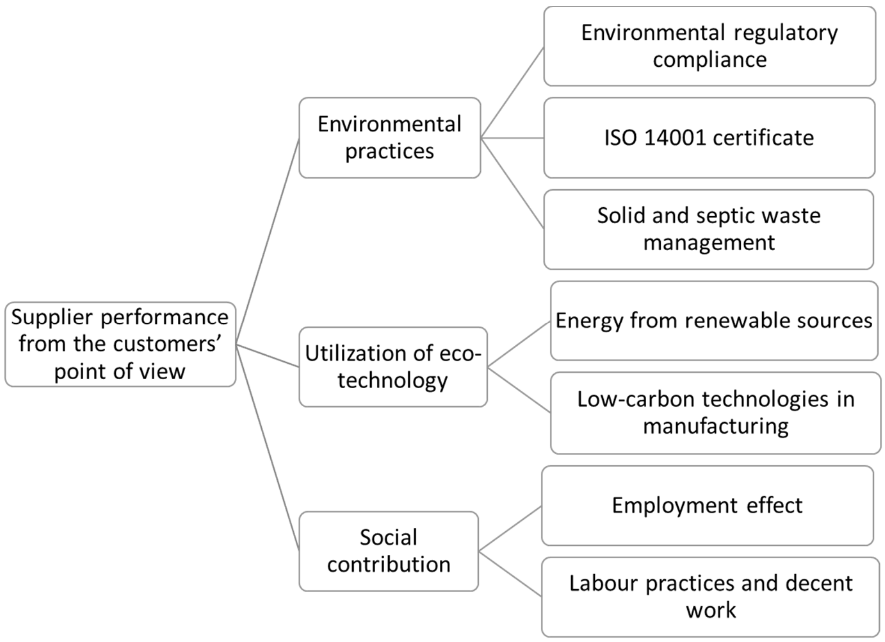


*Figure 31. Framework composed by three criteria and seven sub-criteria are used to compare among suppliers in industrial symbiosis* (Afshari *et al.*, 2020).

Here the indicators are evidently derived from green procurement performance indicators, used to prioritize suppliers based on their values perceived by customers. Environmental and social impacts are then included in the defined social value index.

### 3.5.3 Distributed energy systems and energy-based UIS approach

The social impacts of energy projects have become increasingly important as the energy production modes shift from a centralised model, somehow distant from most people's everyday life, to a distributed one involving new energy technologies, and mainly renewable technologies, both at utility-scale and small-scale level. Thus, the implementation of a new energy project, particularly in democratic countries, requires public engagement. The public perception of new energy technologies or infrastructure strongly influence the project feasibility at local level. This is true both for technologies impacting the local landscape such as wind farm, and for apparently harmless devices such as smart metering (Boudet, 2019). The next Table 42 lists some of the benefits/disadvantages as perceived by the public.

| Technology | Benefits/advantages | Risks/disadvantages |
|---|---|---|
| Rooftop solar | Reduced air pollution | Initial investment |
| | Carbon savings | Toxicity/flammability of materials |
| | Electricity bill reduction | |
| | Tax advantages | |
| Utility-scale solar | Economic development | Ecosystems impacts |
| | Tax revenue | Visual impacts |
| | Landowner and/or community compensation | Impacts to property values, electricity rates, tourism and so on |
| | Reduced air pollution | Toxicity/flammability of materials |
| | Carbon savings | Intermittency |
| Utility-scale wind | Economic development | Ecosystems impacts |
| | Tax revenue | Visual impacts |
| | Landowner and/or community compensation | Impacts to property values, electricity rates, tourism and so on |
| | Reduced air pollution | Toxicity/flammability of materials |
| | Carbon savings | Intermittency |
| Smart meters/grids | Consumer savings through feedback, better management of energy usage | Individual privacy, hacking |
| | Carbon savings | Cyber-terrorism |
| | Automated demand-side response | Trust in automation, algorithms |
| | A solution to renewable energy's intermittency and grid management | Health from wireless networks |
| | Peak demand management | |
| | Enhanced resilience | |

*Table 42. Commonly cited risk–benefit perceptions of some renewable energy technologies (adapted from (Boudet, 2019)); smart meters and grids are included in the table since the use of such technologies is associated to RES.*

As previously discussed, industrial energy symbiosis projects can respond to some of the disadvantages or risks perceived by local communities, confining the energy facilities within a familiar industrial structure.

On the other hand, the new distributed and integrated energy system brings along the widening of the energy stakeholders' community: through the decentralized energy production, "consumers", both households and businesses, are called to a more active role along the energy value chain. They can act as "prosumers", being simultaneously energy producers and consumers. This new role requires new knowledge, awareness and active engagement in the decision-making processes. Moreover, as observed also by social scientists studying sustainable behaviour and low-carbon transitions, social considerations become crucial into the energy field that has traditionally been dominated by techno-economic models and explanations. In fact, as the public is often unfamiliar with energy technologies, recent social science research suggests that knowledge alone is not enough to create a positive attitude towards new technology (Boudet, 2019).

Within this framework, renewable energy communities, as defined in the RED II (described in the section 2.2 of Chapter 2) bring about both the energy transition concept, through the RES integration, and social innovation as they imply a shift in energy consumers' behaviour and the empowerment of energy consumers. As a community-driven initiative, it allows to approach new technologies overcoming some major negative perceptions and building up a collective view focusing on possible advantages.

According to the study of (Caramizaru and Uihlein, 2019), reviewing the European ongoing community-based energy projects, the engaged communities clearly share a common view, considering economic benefits but also social and environmental culture and goals; the policy related support schemes foster the projects uptake; each community shares some local specific motivations, such as the willing of investing in sustainable infrastructure or green energy. According to EU legislation, the community energy initiatives aim at creating social innovation, brought about both by the community involvement in the energy projects, and to the community itself (Table 43).

| **Benefits brought by community** | **Benefits for citizens and the local community** |
|---|---|
| *Local value*: Local sustainability projects can achieve energy independency, reduce carbon emissions and fuel poverty, as well as contribute to the local economy (local jobs, hold financial resources) | Participation/ownership, contribution to economic development |
| *Energy citizenship and democracy*: Participation in renewables ownership and decision-making | Enhanced lifestyle, pro-environmental attitude |
| *Generating financial returns for the community*: Community assets (wind turbines, solar panels) are used to generate profits locally (including jobs). Surpluses can be reinvested in community benefit funds and other activities. | Low-cost energy bills |
| *Education and mobilisation of citizens:* Empowering citizens towards joint action for combating climate change alongside municipalities and local authorities. | Social cohesion |
| *Social cohesion*: creating a community feeling, trust. | Education |
| | Acceptance & awareness |
| | Tackling energy poverty, through energy justice goals |
| | Regenerating local economy |
| | Well-being & health |
| | Local job creation & skills |

*Table 43. Social innovation framework for the energy communities (Caramizaru and Uihlein, 2019).*

Consistently with the previous scheme, the social criteria previously introduced (chapter 2-section 4) include the *job creation* and *improvement of educational level*, the *social acceptance*, the *sufficient energy supply to meet basic needs*, and the *social benefits*. The last two reviewed indicators, *safeguards* and *advanced performance*, are linked to the technological characteristic of the facilities.

### 3.5.4 Social criteria for energy-based urban-industrial symbiosis

The urban-industrial energy symbiosis integrates features derived from the distributed energy projects, the industrial symbiosis approach, and the energy communities approach. Aspects like the inclusion of consumers in the energy supply chain, as well as the increasingly positive approach to new technologies must be taken into account in a criteria system for the assessment of the UIS projects.

A set of social indicators for the sustainability assessment of energy-based urban-industrial symbiosis projects is proposed here (Table 44).

| Social criteria | Indicator | Unit |
|---|---|---|
| Social acceptance | Participation to the project | # |
| | Organization joint workshops/events within the UIS system | # |
| | Participation to joint organized events within the UIS system | # |
| Social benefits | Jobs created | # |
| | Investments in innovation/new businesses | €/# |
| | Education/improved skills: workers trained (or hours of training per worker) | # |
| | Revenue/Energy bills reduction | € |
| | Improved welfare for alleviating energy poverty | € |
| | Investments in joint infrastructure supporting community and workers (kindergarten, mensa, canteen, cafeteria, mobility) | € |
| | Investments in organized social activities | € |
| Quality of life: environmental, health, and safety conditions | Rate of sick citizens/workers (e.g. due to lung diseases) | % |
| | Rate of work accidents | % |
| | Rate of environmental accidents | % |
| Social responsibility | Attitude to green purchasing | € |
| | Social responsibility at technologies supply side | € |
| | Compliance with environmental regulation | # |

*Table 44. Set of social criteria proposed for energy UIS projects.*

The selected criteria provide an overarching view of the social sustainability goals for an energy UIS project. The set does not consider the perceived quality of life, safety, health and environment improvements, that can be investigated through surveys.

According to reviewed literature (see for instance (Wang *et al.*, 2009)), the most important social criteria in an energy project involving new technologies are the *social acceptance* criterion, since any opposition (due to perceived risks) can heavily delay the project implementation, and the *job creation* criterion, a benefit providing local long-term prosperity. In the proposed set, the *social acceptance* criterion is expressed through the active participation to the project and project related activities. This is a qualitative criterion, usually investigated through surveys carried out in the local community in order to get some quantitative indicators.

# 4 WASTE OR RESOURCE? AN URBAN-INDUSTRIAL SYMBIOSIS PROJECT FOR THE CITY OF CORREGGIO

The city of Correggio (RE), a historical town located in the Emilia Romagna region in the North of Italy, is surrounded by a territory where modern farms coexist with industrial districts made up of small and medium-sized enterprises. It is located in the Po Valley, in the North of Italy, one of the most polluted area in Europe. So, there is a significant need to reduce the atmospheric emissions due to the energy consumption. The share of regional energy consumption attributable to the industrial sector is 30%, while the tertiary sector weights for 18%. Therefore, the improvement of the regional industrial energy system will involve impacts at local and regional scale, in terms of GHG emissions reduction and energy saving.

The local authorities are going to introduce an urban regeneration strategy according to the *Strategy for urban and ecological-environmental quality and assessment of environmental and territorial sustainability of the general urban plan*, including the requalification of an industrial district. In cooperation with the Department of Science and Methods of Engineering of the University of Modena and Reggio Emilia, the urban-industrial potential synergies will be included in the project. The combination of the UIS project and the local planning strategy aims at improving the impact of both the local industrial chain innovation triggered by the symbiosis approach and the urban transition to sustainability (Bian *et al.*, 2020).

The design of the cooperation project is described hereafter. The project consists of two levels of analysis. The first step (section 4.1) concerns the analysis of the energy resource with the evaluation of possible industrial energy symbiosis projects including the use of energy from renewable sources; the developed model will be applied to the data collected from participating firms to highlight what the economic, environmental and social advantages of energy symbiosis projects may be. The more general level (section 4.2) extends the analysis to the surrounding urban area, considering the urban-industrial symbiosis approach in relation to urban metabolism. The main objective associated with this level of study is to provide a local impact assessment tool that projects of industrial symbiosis and / or urban-industrial symbiosis may have in terms of environmental benefits, saving resources and reducing the environmental impact, economic and competitive advantages for the companies involved, benefits for the community (e.g. more jobs).

## 4.1 OPPORTUNITIES FOR INDUSTRIAL ENERGY SYMBIOSIS INTEGRATING RES IN THE INDUSTRIAL AREA B

Correggio is surrounded by three industrial areas, strictly correlated with the urban pattern. The strategies for improving UM focusing on energy flows include the implementation of industrial and territorial low carbon strategies, a challenge at EU level and Regional level. Within the municipal territory, the energy consumption data[18] for the year 2018 were as in Table 45:

| Sector | Energy type | Energy consumption (MWh) |
|---|---|---|
| Residential and tertiary | Thermal | 244,797.18 |
| | Electricity | 85,239.85 |
| Industry | Thermal | 262,021.64 |
| | Electricity | 117,525.67 |
| Transportation | - | 302,248.91 |

*Table 45. Energy consumption data for the Correggio municipal territory.*

[18] Data retrieved from the Osservatorio Energia Emilia-Romagna (https://dati.arpae.it/group/osservatorio-energia-emilia-romagna )

The clear commitment of regional administration in supporting businesses on multiple fronts to reduce their carbon footprint, fosters interventions also at local level.

### 4.1.1 Local Energy Policies supporting Renewables Uptake

Some industrialized areas, like the Emilia Romagna Region, need to further reduce the atmospheric emissions due to the energy consumption, mainly in industrial districts located in highly populated zones. Emilia Romagna established the goals of reducing energy consumption by 20% in industry productive sector and by 25% in service companies, and to improve RES installation in industrial districts by 20% to obtain a GHG emissions reduction by 20%, to 2020. However, since the regional trend of GHG emissions reduction, energy saving and share of renewable energy is in line with achieving EU targets (current targets' value respect to 1990: -12%, -23%, +12%), the need of increasing the number of energy-saving related project in businesses have been highlighted at regional level[19] where a poor diffusion of the culture of energy efficiency and energy-saving within companies has been observed.

The Regional Energy Plan to 2030[20] sets an increase target for energy efficiency in the industrial sector of about 4% per year and promotes the improvement of the energy performance of industrial areas, production processes and products through:

- supporting the shift to electrification, and in particular to electricity self-production from renewable sources;
- supporting the exploitation and recovery of thermal waste available under the processes and existing industrial areas and the diffusion of high efficiency cogeneration;
- supporting the diffusion of energy control and management systems (energy diagnosis, ISO 50001 management systems, etc.);
- the activation of financial instruments that optimize resources with respect to the profitability of investments;
- supporting the development of APEAs with particular attention to the development of good practices in terms of energy saving and development of renewable sources also through the adoption of industrial symbiosis strategies.

In addition, the regional Smart Specialisation Strategy sets specific objectives concerning the pathway to more sustainable energy use, namely the promotion of energy efficiency measures, the promotion of renewable energy, and the development of smart grid and storage systems at local level.

### 4.1.2 Strategies for the conversion of existing industrial parks into eco-industrial parks

The local businesses located inside the chosen industrial area B will be supported in a learning path towards an improved awareness of effective and innovative technological solutions to enhance their energy related performances. Moreover, they will be involved in the feasibility study and co-design activities of an urban-industrial project.

Considering the existing industrial area, the analysis of the factors potentially enabling the conversion of industrial sites into eco-industrial parks has been performed.

According to the literature, the creation of eco-industrial networks within industrial parks requires a systemic transformation, and the setup of strategies addressing technological, cultural, and regulatory issues. If the businesses' willingness to cooperate is an essential requisite, the local environment plays an essential role in fostering the uptake of symbiosis projects in terms of providing knowledge support, a shared commitment towards sustainability goals, supporting regulations and policies (Yedla and Park, 2017; UNIDO, 2019).

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[19] Il Piano Energetico Regionale 2030: policy attuate e monitoraggio dei risultati raggiunti, luglio 2018, ERVET Emilia-Romagna Valorizzazione Economica Territorio S.p.A. per Regione Emilia Romagna.

[20] Piano Energetico Regionale 2030 Emilia-Romagna, 2016

#### *4.1.2.1 Policy and administrative level*

As discussed in the Chapter 1, national policy instruments promoting resources conservation and circularity of products, as well as supporting sustainable industrial development demonstrated their effectiveness in the UK, China, Korea, Japan, among others.

At the level of local administrations, they can act as initiators promoting firms' involvement, fostering awareness raising and capacity-building through the involvement of research institutions or universities and other stakeholders, and providing facilitated regulations and public-private partnerships opportunities for creating the exchanging infrastructure.

#### *4.1.2.2 Park level*

Together with the firms' strong commitment and sharing of goals, when a park managing body is not available, a "champion" can motivate the other participants and drive the conversion process. A strategic approach to decision-making related to park management and to recover and share costs and benefits associated with common infrastructure, utilities and park services must be set up.

Participants must be enabled to recognize the full set of benefits going beyond return-on-investment: improved environmental and social performance, risk mitigation, improved productivity, etc. Moreover, performance monitoring and benchmarking should be implemented to guarantee long-term cooperation and future developments.

#### *4.1.2.3 Social measures*

The building up of an interface between eco-efficiency in industries and local communities, can promote the citizens' acceptance and their involvement in sustainable practices, guaranteeing long-term sustainability of the eco-industrial development.

### 4.1.3 The project – stage 1

The aim of the first step of cooperation project is to analyse the opportunities of improving the energy performances and sustainability of the firms located within the industrial area B, also through the implementation of energy symbiosis networks integrating renewable energy technologies. Local authorities will be supported in the improvement of the local energy programs aimed at promoting and increasing the implementation of energy efficiency measures and low carbon strategies in the industry sector, and at the industry districts level. On the other hand, with the local authorities playing the *facilitator* role, the companies will be:

- guided in improving the awareness and internal expertise on the available and innovative technologies allowing energy efficiency solutions, demonstrating the benefits resulting from energy saving solutions and collective energy projects,
- oriented towards the creation of energy-independent industrial networks, and
- helped in exploiting financing opportunities offered by regional development policies and programmes for energy efficiency and RES related investments, that can result advantageous for local communities as well.

Stakeholders' engagement on energy themes (energy efficiency, energy savings, renewable energy technologies) allow to analyse the diverse expectations and set common sustainability goals (Figure 32).

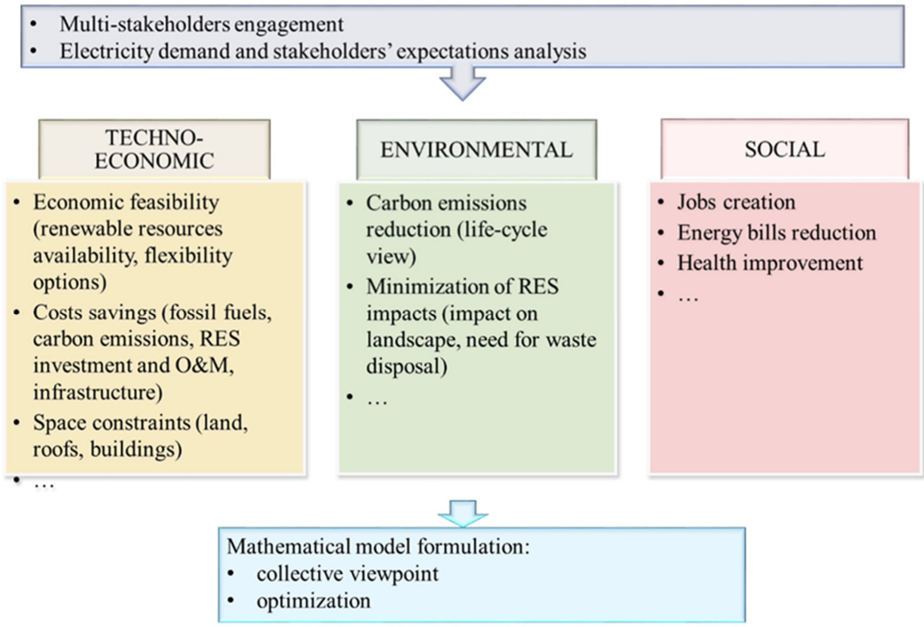


*Figure 32. Project development framework.*

An energy-focused questionnaire has been drafted Table 46, based on energy diagnosis framework, (Horbach and Rammer, 2018; Patricio *et al.*, 2018; Lu *et al.*, 2020), and UBIC project[21], to extensively map the energy consumption of the companies located within the industrial area. The energy mapping will provide the input data for the developed mathematical model. It will be applied to highlight what the economic, environmental and social advantages of energy symbiosis projects may be.

The purpose of the interviews is to collect basic company information, such as the industry sector and number of employees; the main data regarding the energy consumption and energy management information; some information about the willingness to cooperate within the industrial area to open a discussion on the energy-based IS and UIS opportunities with wider stakeholders.

The involvement of the firms form the very first stages of the project is essential to build trust and lead companies to make available detailed data on internal energy consumption and, hopefully, information about process streams which they may be reluctant to share.

[21] Urban Baltic Industrial Symbiosis project (funded by the Interreg South Baltic - ERDF Programme) https://ubis.nu/

<table>
<tr><td colspan="13">GENERAL INFORMATION ABOUT THE COMPANY</td></tr>
<tr><td>Name of company:</td><td colspan="12"></td></tr>
<tr><td>ATECO[22] code:</td><td colspan="12"></td></tr>
<tr><td>Principal product(s) or service(s):</td><td colspan="12"></td></tr>
<tr><td>No. employees:</td><td colspan="12"></td></tr>
<tr><td>Turnover:</td><td colspan="12"></td></tr>
<tr><td colspan="13">ENERGY DATA</td></tr>
<tr><td>Does the company undergo energy audit (diagnosis)?</td><td colspan="6">□ YES</td><td colspan="6">□ NO</td></tr>
<tr><td>Annual electricity consumption</td><td colspan="12">kWh (year ……………………)</td></tr>
<tr><td>Monthly electricity consumption</td><td>Jan</td><td>Feb</td><td>Mar</td><td>Apr</td><td>May</td><td>Jun</td><td>Jul</td><td>Aug</td><td>Sep</td><td>Oct</td><td>Nov</td><td>Dec</td></tr>
<tr><td>Yearly energy consumption</td><td colspan="4">Main activities (production processes):</td><td colspan="4">Auxiliary:</td><td colspan="4">General services:</td></tr>
<tr><td>Energy carriers (yearly consumption)</td><td colspan="3">Electrical energy</td><td colspan="3">Natural gas</td><td colspan="3">Diesel</td><td colspan="3">Biomass</td></tr>
<tr><td colspan="4">Does the company apply energy efficiency strategies? If so, which ones?</td><td colspan="9"></td></tr>
<tr><td colspan="4">Has any energy waste been assessed?<br>- in auxiliary services<br>- in buildings<br>- in production processes</td><td colspan="9"></td></tr>
<tr><td colspan="4">Is any energy surplus produced? (e.g. steam / heat)</td><td colspan="9"></td></tr>
<tr><td colspan="4">Does the company apply emission reduction strategies? If so, which ones?</td><td colspan="9"></td></tr>
<tr><td colspan="4">Are there spaces (offices, warehouses, production areas) that are underused and could be shared with other companies?</td><td colspan="9"></td></tr>
<tr><td colspan="4">Are there electrical connections or gas, or steam lines between companies?</td><td colspan="9"></td></tr>
<tr><td colspan="4">Does the company use renewable energy? If so, what share of the company's energy demand is produced by the plant?</td><td colspan="9"></td></tr>
<tr><td colspan="4">Do you know the owners (or CEOs) of the other companies in the industrial area?</td><td colspan="9"></td></tr>
<tr><td colspan="4">Do you think it feasible to organize electric and shared transport systems within the industrial area?</td><td colspan="9"></td></tr>
<tr><td colspan="4">Do you think it possible / interesting to participate in collective projects (with other companies in the area) to improve the energy efficiency of your company or reduce harmful emissions to the climate?</td><td colspan="9"></td></tr>
</table>

*Table 46. Energy related questionnaire for the enterprises located within in the industrial area B.*

## 4.3 COMBINING THE URBAN METABOLIC APPROACH AND THE UIS APPROACH

This second stage concerns the building up of a participatory process to engage all the stakeholders at community level, to raise awareness on the sustainability themes and set common goals, and the tracking of energy and material flows in the considered urban and industrial area to evaluate how to reduce the environmental impacts by redesigning closed loops.

### 4.3.1 Stakeholders' engagement

As previously discussed, the stakeholders' active participation in the EIP and IS development process, as well as in energy planning, is a key factor to assure project's success.

A list of influential stakeholders for EIP development extracted from the literature is presented in the Table 47 (Heeres, Vermeulen and de Walle, 2004; Pilouk and Koottatep, 2017). The main role that each stakeholder can play in the development process (based on case studies) is highlighted: project initiator or commissioner (Initiator), project manager (PM), member of the planning group (P.G. member), active participant (Active P.) in project development (not financial), financial supporter (Financial S.), consultant to the project (Consultant), infrastructure and service providers (Tech. Support).

| Stakeholders | Initiator | PM | P.G. member | Active P. | Financial S. | Consultant | Tech. Support |
|---|---|---|---|---|---|---|---|
| **National government** | | | | | X | X | X |
| **Regional government** | X | | X | | X | | X |
| **Local government** | X | X | X | X | X | | X |
| **Chamber of Commerce** | X | X | | | | | |
| **Companies** | | | | X | | X | |
| **Entrepreneurs' Association** | X | X | X | | | | |
| **Educational Institutions** | | | | X | | X | |
| **Consultants agencies (architecture, engineering, environmental management,…)** | | | | X | | X | |
| **Labor unions** | | | | X | | X | |
| **NGO – Environmental** | | | | X | | X | |
| **Local residents** | | | | X | | X | |

*Table 47. Stakeholders in EIPs.*

It results from the previous table 47 the high level of involvement of the local authorities, covering almost all roles, and the participation of all the stakeholders as active partners.

As far as concern the main stakeholders' categories typically involved in energy projects involving RES, they are listed in the next Table 48.

| Stakeholder type | Description /role / needs |
|---|---|
| Public body & policy making | Legal framework, subsidies, community wellness |
| Regulation | Market rules, grid connection rules, … |
| Municipal utility/ Utility company | (Local) generation, service, end user, infrastructure |
| Network operator | Grid operation, infrastructure |
| Civil society (Local community, Environmental conservation groups,...) | Issues: Social acceptance, energy bill, health, environmental impacts |
| Research- University | System analysis and modelling, energy market modelling, battery research, … |
| Renewable technologies production/retail | System integration, manufacturing, planning, operation |
| Battery manufacturer | Production, R&D, sales, system integration, operation |
| Automotive sector (electric mobility) | System integration (electric vehicle), production, operation |
| Consultants | Expertise |
| Labor union | New jobs, labor practices and decent work, skills improvement |
| RES associations | RES integration promotion |

*Table 48. Stakeholders in energy projects involving RES.*

### 4.3.2 The project- stage 2

The main planned activities are:

1. Stakeholders' engagement, knowledge sharing and sustainable goals establishment.
2. Survey and inventory of the major physical flows of the industrial area, to evaluate the willingness to participate in industrial symbiosis projects and the potential synergies (Table 49). The purpose of the questionnaire is to collect the following data (Simboli, Taddeo and Morgante, 2014; Leigh and Li, 2015; Patricio *et al.*, 2018):
    - -basic information about the company (number of employees and annual production);
    - -types and quantities of resources used in production and who supplied them;
    - -types, quantities and presence of waste and by-products (and potential sources of contamination);
    - -logistics information;
    - -relations with stakeholders;
    - -methods of managing waste and by-products, with the related costs.
3. Inventory of the major physical flows of the urban area, to evaluate how to rationalize resources consumption and the resources savings options, in a circularity perspective.
4. Formulation of possible actions on the basis of feasibility studies and overall sustainability evaluation.

| GENERAL INFORMATION ABOUT THE COMPANY | |
|---|---|
| Name of company: | |
| ATECO code: | |
| Principal product(s) or service(s): | |
| No. employees: | |
| Turnover: | |

| INDUSTRIAL SYMBIOSIS SURVEY | |
|---|---|
| Can you briefly describe the production process? | |
| What kind of raw materials are used?<br>Where are the raw materials purchased and in what quantities?<br>Do you know of any waste that can replace these raw materials? | |
| What are the quantities produced each week / month / year?<br>What kind of by-products and / or waste are produced during the process? In what quantity?<br>Is the quantity of these by-products / waste constant over time?<br>How are by-products and waste currently disposed of?<br>Are you aware of possible uses of by-products as raw materials? | |
| Are there any kind of extra logistics (e.g. packaging, warehouse) required for your product? Are there any wastes produced during those steps?<br>How do you deliver your products to your customers? | |
| Do you know what are industrial symbiosis partnerships? | ☐ Yes - What is the main hinder for you to take part in industrial symbiosis? What could catalyse your involvement in an industrial symbiosis partnership? |
| | ☐ No - Would you want to take part of any symbiosis? Why/Why not? (after introducing the concept of industrial symbiosis) |

*Table 49. IS related questionnaire for the enterprises located within in the industrial area B of Correggio.*

# CONCLUSIONS

The presented study shows how the low-carbon transition of industry can be boost both by technology innovation, providing energy efficiency and saving options, and by unconventional and collective energy strategies implemented within the industrial symbiosis framework. The eco-industrial parks model, that support the reduction of the environmental footprint of the involved firms, promotes the sustainable use of energy, and represents a suitable cooperative model for fostering the integration of RES in the industrial system.

After the analysis of the options, existing solutions and modelling methods for collective energy strategies, the thesis organizes the knowledge on energy sustainability in industrial parks showing viable solutions and the effectiveness of RES integration within EIPs for reducing the carbon footprint of industry. Four main pathways have been identified 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 and management of energy, and shared building services and utilities are viable solutions for improving RES uptake at the industrial level.

A model for the optimization and evaluation of the energy symbiosis including the integration of RES within the EIPs have been developed and discussed. The model analyses the economic advantages and the environmental impact (carbon emissions) of energy symbiosis when RES are used to satisfy a percentage of the energy demand within EIPs. It presents a multi-stakeholder perspective, comparing the single firm point of view, the environmental optimization only and the EIP collective perspective, building up different scenarios that provide to single firms' and parks' managers relevant information for supporting decision making regarding the economic sustainability and the environmental impacts of the energy synergies. The key results can be summarized as follows:

- When single firms joining the EIP decide to satisfy an amount of internal electrical energy demand in a more sustainable way, they can get economic convenience in buying renewable energy.
- The environmental scenario shows that there is room to improve the carbon footprint of industry, though a trade-off between carbon reduction and economic convenience must be reached.
- Lastly, the collective point of view shows a more efficient management of the energy from eco-plants and energy surplus from supplier firms, balancing the buyers and suppliers needs.

Due to the strong interactions between the industrial sites and the neighbor territory, the advantages of energy symbiosis networks between industrial and nearby urban are investigated in the last chapter of the thesis. The analysis of the urban-industrial symbiosis approach emphasizes the existing links with the urban metabolism research field and the sustainable cities planning area. The application of the industrial and urban-industrial symbiosis model is then designed to be included in the urban regeneration strategy of the city of Correggio. The multi-stakeholder involvement and engagement is the prerequisite for implementing such project and the inclusion of social impacts in the evaluation model will be fundamental.

Considering that the main limit of this thesis is that more experimental research is need to stress the model, this project, that will evaluate the suitability and sustainability of energy strategies both within an industrial area and in urban-industrial perspective, will apply the developed model to the case study, allowing to improve it including aspects that can emerge from the case. Two main key issues, already come to light during the performed research, will be deeply investigated with the help of the project's stakeholders:

- the sustainability criteria framework for the evaluation of energy projects within EIPs, in particular considering the transformation of existing industrial sites into eco-industrial parks, and
- the social impacts of energy clustering projects, considering both IS and UIS.

The development of a social index will be evaluated to include the social perspective in the model for the evaluation of the energy symbiosis including RES.

The research carried out during this PhD work, lead to the publication of the following papers (partially re-elaborated in this thesis):

- Butturi M.A., Lolli F., Balugani E., Gamberini R., Rimini B., Distributed renewable energy generation: a critical review based on the three pillars of sustainability, Proceedings of the XXIII Summer School "Francesco Turco" – Industrial Systems Engineering, Palermo 12-14 September 2018.
- M.A. Butturi, F. Lolli, M.A. Sellitto, E. Balugani, R. Gamberini, B. Rimini, *Renewable energy in eco-industrial parks and urban-industrial symbiosis: A literature review and a conceptual synthesis*, Applied Energy 255 (2019) 113825.
- M. A. Butturi, M. A. Sellitto, F. Lolli, E. Balugani, A. Neri (2020). *A model for renewable energy symbiosis networks in eco-industrial parks*. Presented at 21st IFAC World Congress, in press.
- S. Marinelli, M. A. Butturi, B. Rimini, R. Gamberini, S. Marinello (2020). *Evaluating the environmental benefit of energy symbiosis networks in eco-industrial parks*. Presented at 21st IFAC World Congress, in press.
- S. Marinelli, M.A. Butturi, E. Balugani, F. Lolli, B. Rimini (2020). *Environmental benefits of the industrial energy symbiosis approach integrating renewable energy sources*, to be published in the PROCEEDINGS OF THE 25TH SUMMER SCHOOL FRANCESCO TURCO.
- M. A. Butturi & R. Gamberini, Urb*an–industrial symbiosis to support sustainable energy transition*, Int. J. of Energy Prod. & Mgmt., in press. (presented at Sustainable City conference, 22-24 September 2020)

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